AERODYNAMIC SIMULATION TESTS OF RSI PANELS

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INTRODUCTION

During the past several years the concept of protecting the space shuttle vehicle with reusable surface insulation (RSI) has received considerable attention. Most emphasis has been placed on two different fiber systems--mullite and silica. Since convective heating plays such an important role in the thermal response of these materials, many tests have been conducted in arc-heated facilities in an attempt to simulate the space shuttle environment. It became readily apparent that no existing ground-based facility could simultaneously duplicate the correct combinations of scale, enthalpy, pressure, and air chemistry encountered by the shuttle during its entry into the atmosphere. Some tests have been conducted with relatively small samples in laminar, stagnation flows to assess hypervelocity effects on coating response, emissivity changes, and surface catalytic effects. Since it is a well-known fact that the aerodynamic boundary layer affects the heating rate in the vicinity of gaps and steps, this problem has received some attention for laminar flows. Because the boundary-layer flow over a large percentage of the vehicle surface is likely to be turbulent and supersonic, it was apparent that this facet also needed to be simulated.

In order to accomplish this objective, an arc-heated, supersonic turbulent-flow duct facility was developed at the Ames Research Center. This duct, with an internal cross section of 5.08 x 22.9 cm (2 x 9 inches), can accommodate test panels up to 20 x 51 cm (8 x 20 inches) in planform. The first RSI panels to be tested in this facility were obtained through the NASA-Manned Spacecraft Center from three RSI contractors; Lockheed Missiles and Space Company, General Electric Company, and McDonnell Douglas Astronautics. This paper describes the facility and presents the results of preliminary tests performed on 20 x 25.4 cm (8 x 10 inch) panels--the first TPS tests to be performed in this facility.

SCHEMATIC OF AMES 2 X 9 INCH TURBULENT FLOW DUCT FACILITY

(Figure 1)

A schematic of the Ames 2 x 9 Inch Turbulent Flow Duct Facility for evaluating space shuttle TPS is shown in figure 1. This facility consists of a Linde N-15000 arc heater coupled to a water cooled nozzle and test section (Mach Number 3.5). Panel sizes 20.3 x 25.4 cm (8 x 10 inches) and 20.3 x 50.8 cm (8 x 20 inches) can be accommodated in one wall of the test section as shown in the figure. Calorimeters and pressure orifices are located on the opposite wall. Individual calorimeters may be removed and replaced with small, optical ports for viewing the test specimen with an optical pyrometer. In order to reduce the thermal shock associated with starting and stopping the arc-heater, argon is used as a test gas at the beginning and end of each run. This technique is discussed in more detail in figure 3.

SCHEMATIC OF AMES 2×9 INCH TURBULENT FLOW DUCT FACILITY

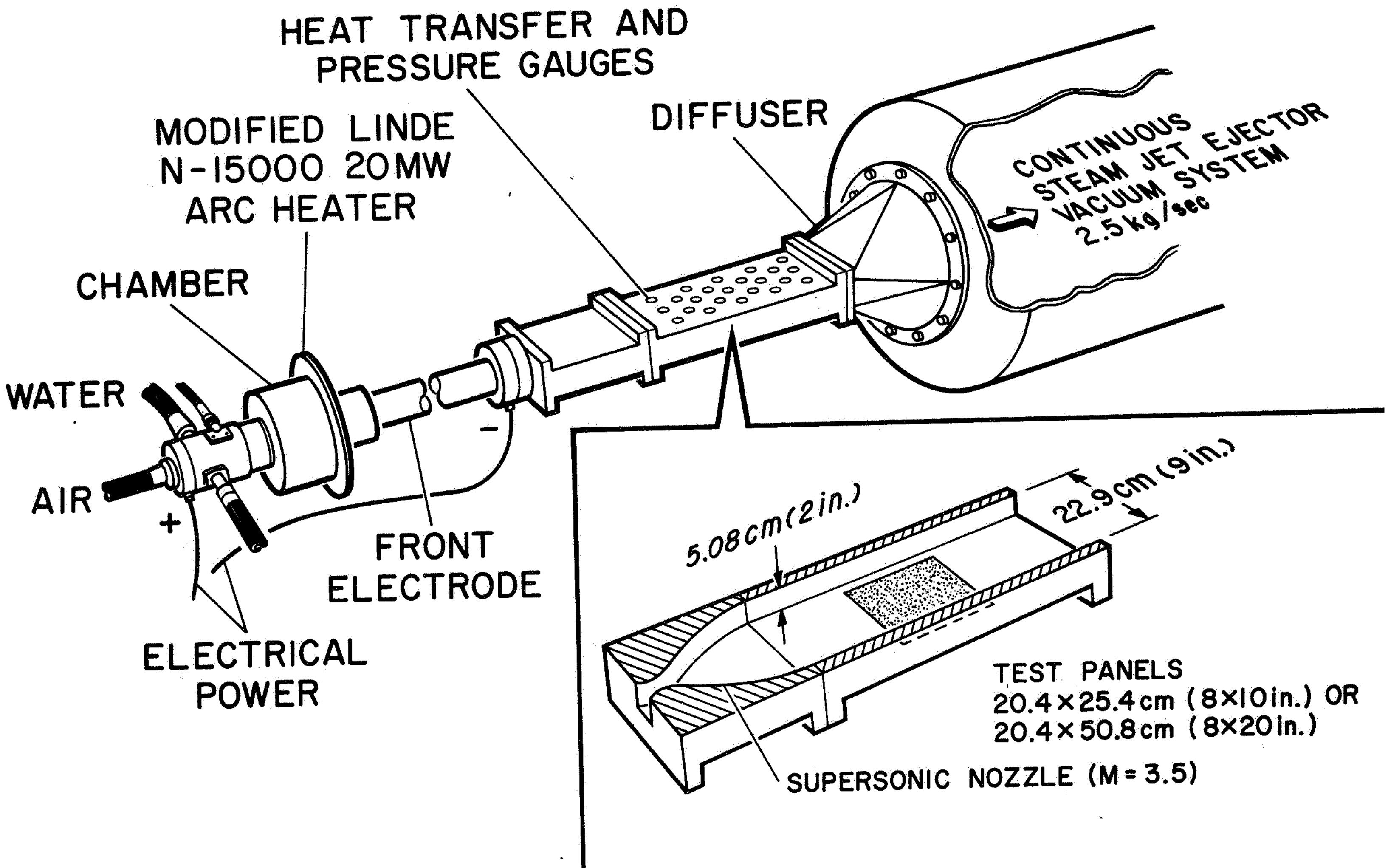


Figure 1

PHOTOGRAPH OF AMES 2 X 9 INCH TURBULENT FLOW DUCT FACILITY

(Figure 2)

A photograph of the facility is shown in this figure. This photograph illustrates the relative scale of the facility and the general arrangement of the associated apparatus and equipment.

PHOTOGRAPH OF AMES 2 x 9 INCH TURBULENT FLOW DUCT FACILITY

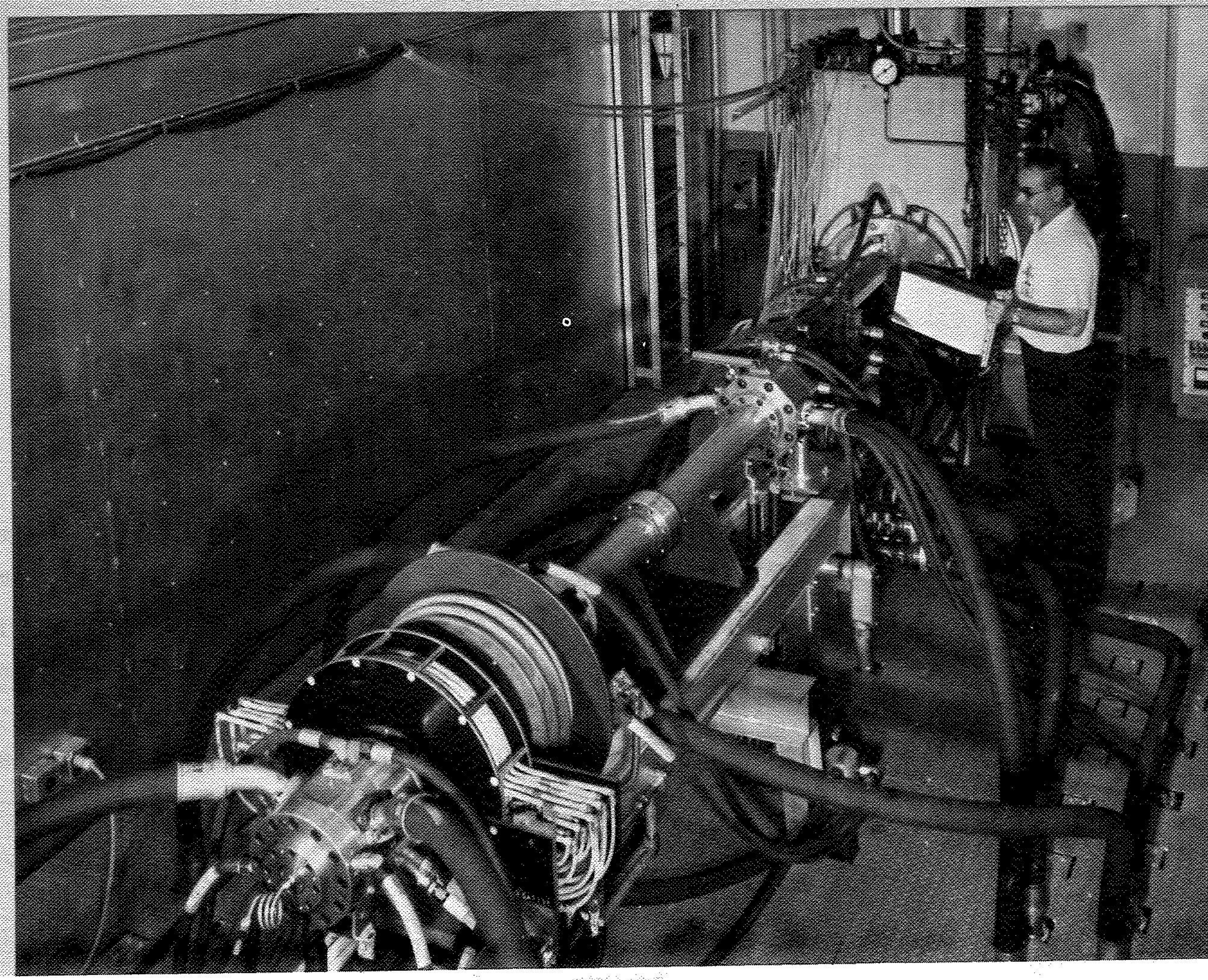


Figure 2

COMPARISON OF HEATING RATES USING AIR ONLY WITH ARGON + AIR MIXTURE

(Figure 3)

When using air as a test gas, there is a minimum heating rate at which an arc-heated facility can be operated. In addition, a spike in the heating rate occurs at the start of the run as shown in this figure. Argon, because of its lower ionization potential, provides a much lower minimum heating rate while also avoiding the undesirable spike at the start of the run. Shown in this figure are the measured cold wall heating rates during simulation of the Space Shuttle Area 2 heating trajectory using air only compared with a similar run where argon and air are used. The simulation of temperatures and pressures is shown in figure 4.

COMPARISON OF HEATING RATES USING AIR ONLY WITH ARGON + AIR MIXTURE

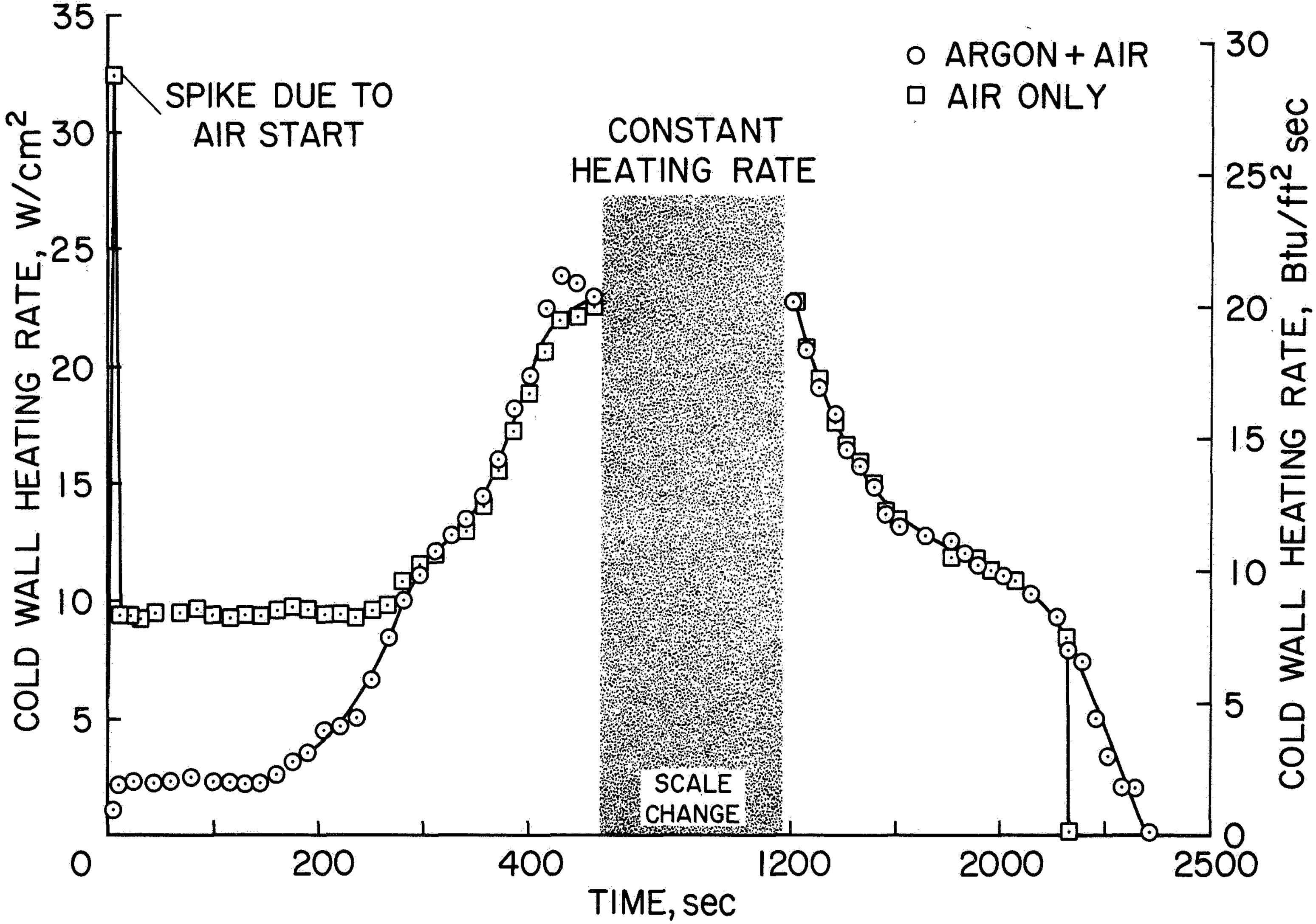


Figure 3

SIMULATION OF SPACE SHUTTLE AREA 2 TRAJECTORY

LOCKHEED LI-1542 PANEL

(Figure 4)

The measured temperatures and pressures for two separate tests of the Lockheed LI-1542 panel are shown in this figure and compared with those specified for the NASA-MSC Area 2 trajectory. At the start of the tests, nearly pure argon is used to avoid the high heating rate associated with starts using air. The maximum rate of change of temperature with time ($\dot{T}$)occurred at the start and was measured to be 17°K/sec (30°F/sec). Air is then introduced and the air/argon ratio is increased. Finally, the arc heater is operating on air alone. Variation of arc current and pressure provide the necessary control of heating rate and temperature during the high heating part of the trajectory and argon is reintroduced to realistically produce the lower heating completion of the trajectory. The simulation of temperature during the runs is good. The simulation of pressure is high in the early part of the trajectory and low in the later part. The test enthalpy at the peak temperature of simulation is 6.2 MJ/gm (2700 Btu/lb). At the end of the simulation, the arc heater is turned off and the ambient pressure is held at a low level (about 1000 N/m^2 or 0.01 atm). The test panels are allowed to cool by radiation, internal conduction, and the small amount of free convection that exists at the low ambient pressures.

SIMULATION OF SPACE SHUTTLE AREA 2 TRAJECTORY

LOCKHEED LI-1542 PANEL

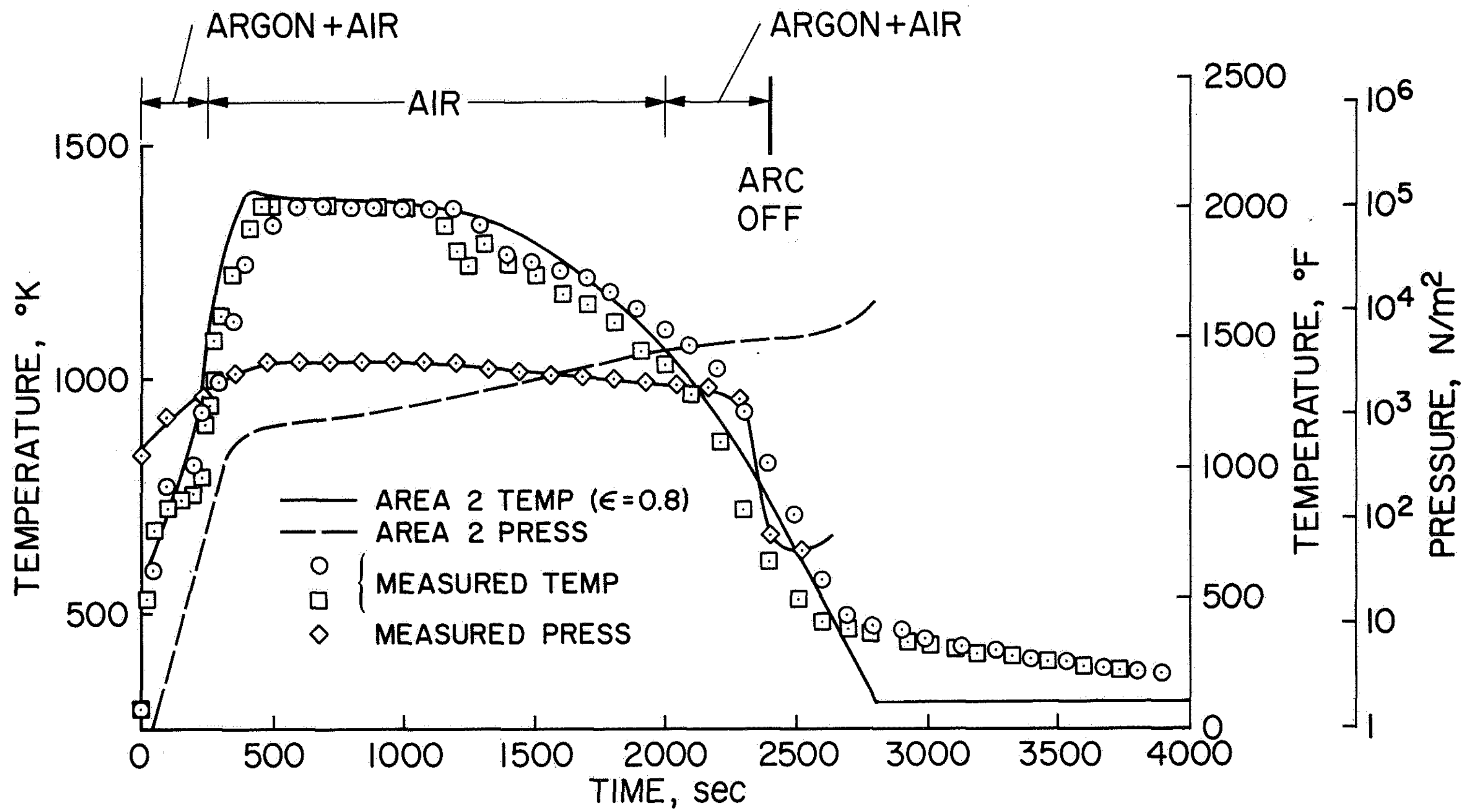


Figure 4

TYPICAL 2 X 9 INCH DUCT TURBULENT BOUNDARY LAYER PROFILES

(Figure 5)

Total pressure surveys were made in the 2 x 9 Inch Duct to characterize the boundary layer flows over the RSI test panels. Results of a typical survey are shown on the left of figure 5 for a total enthalpy of 3.7 MJ/kg (1600 Btu/lb) and a static pressure of $3.5 \times 10^3 N/m^2$ (0.035 atm). Although this stream enthalpy level was lower than that during the panel tests, the measured boundary layer characteristics are probably typical of those occurring at the test conditions. A tantalum-tipped, water-cooled probe moved by a remote controlled traversing mechanism was used to obtain the survey data. No boundary layer temperature profiles were measured because of the high stream temperatures, and the Crocco relationship between total temperature and velocity was assumed in deriving the typical velocity profile shown on the right side of the figure. The momentum thickness and the displacement thickness are seen to be about 2 mm and 5 mm, respectively, while the total boundary layer thickness is about 20 mm. Also indicated on the figure are the maximum gap width and step height dimensions for the RSI panels, and they are seen to be comparable to the momentum thickness.

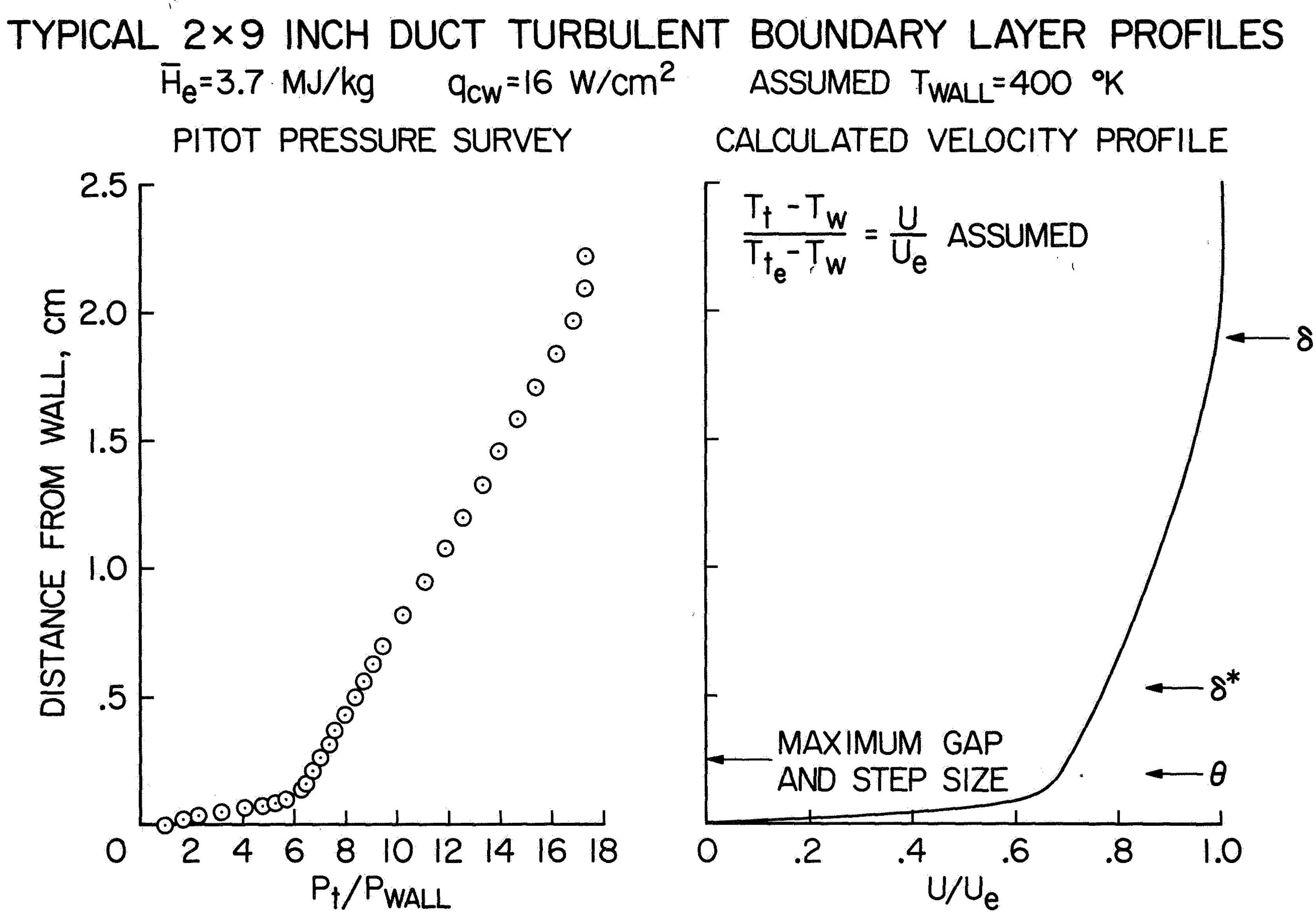

TYPICAL 2×9 INCH DUCT TURBULENT BOUNDARY LAYER PROFILES
$\bar{H}_e$=3.7 MJ/kg q_{cw}=16 W/cm^2 ASSUMED T_{WALL}=400 °K
PITOT PRESSURE SURVEY
CALCULATED VELOCITY PROFILE
DISTANCE FROM WALL, cm
2.5
2.0
1.5
1.0
.5
0
2
4
6
8
10
12
14
16
18
P_t/P_{WALL}
$\frac{T_t - T_w}{T_{t_e} - T_w} = \frac{U}{U_e}$ ASSUMED
δ
δ*
θ
MAXIMUM GAP
AND STEP SIZE
0
.2
.4
.6
.8
1.0
U/U_e

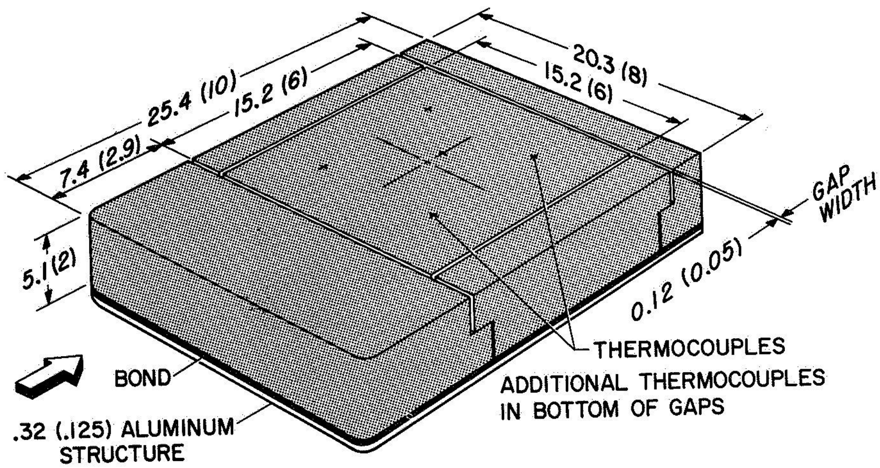
Figure 5

LOCKHEED LI-1542 PANEL

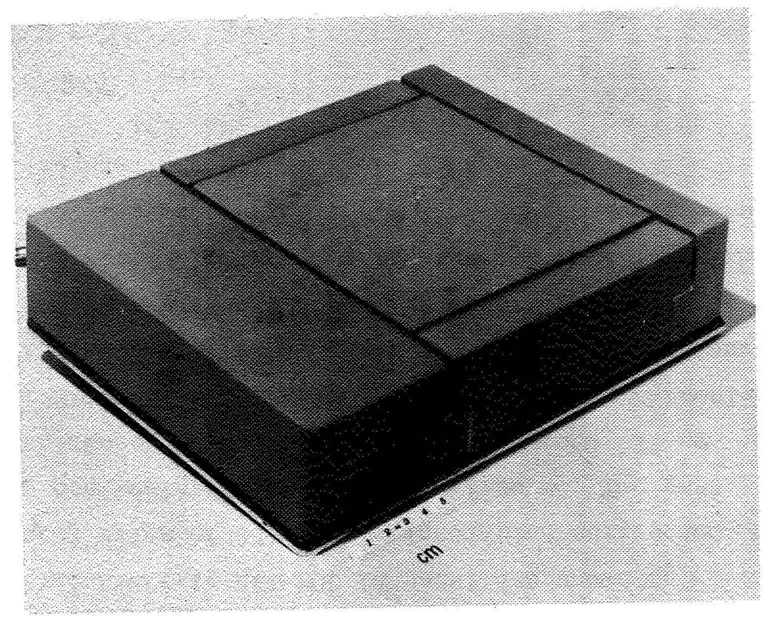
(Figure 6)

An illustration and pre-test photograph of the Lockheed LI-1542 panel are shown in figure 6. The panel consisted of a 15.2 x 15.2 cm (6 x 6 inch) tile of LI-1542 insulation surrounded by smaller tile segments of the same material. The gaps were nominally .13 cm (.050 inch), but varied somewhat with depth and location on the panel. The tiles were bonded to a .32 cm (.125 inch) aluminum plate with RTV 560 adhesive 0.23 cm (.090 inch) thick. There were five platinum-platinum/13 percent rhodium thermocouples located on the surface of the 15.2 x 15.2 cm (6 x 6 inch) tile. Near the center of tile there were three chromel-alumel thermocouples located 1.27 cm (0.50 inch), 2.54 cm (1.0 inch), and 3.81 cm (1.50 inch) below the surface to provide in-depth thermal response measurements. Additional chromel-alumel thermocouples were located at the bottom of the gaps, in the RTV bond, and in the aluminum plate.

LOCKHEED LI-1542 PANEL



a) ILLUSTRATION



b) PRE-TEST PHOTOGRAPH

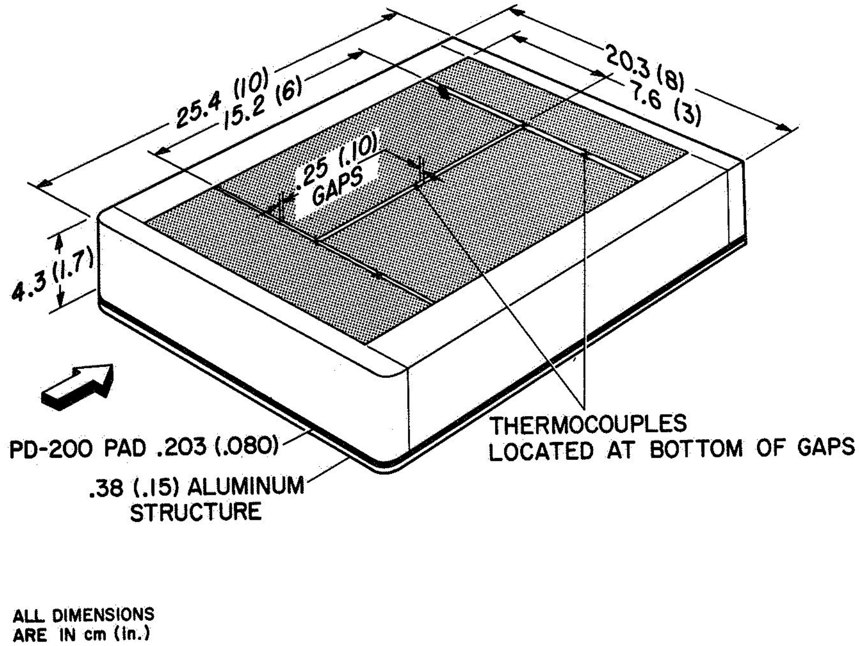
Figure 6

GENERAL ELECTRIC REI-MOD 1A PANEL

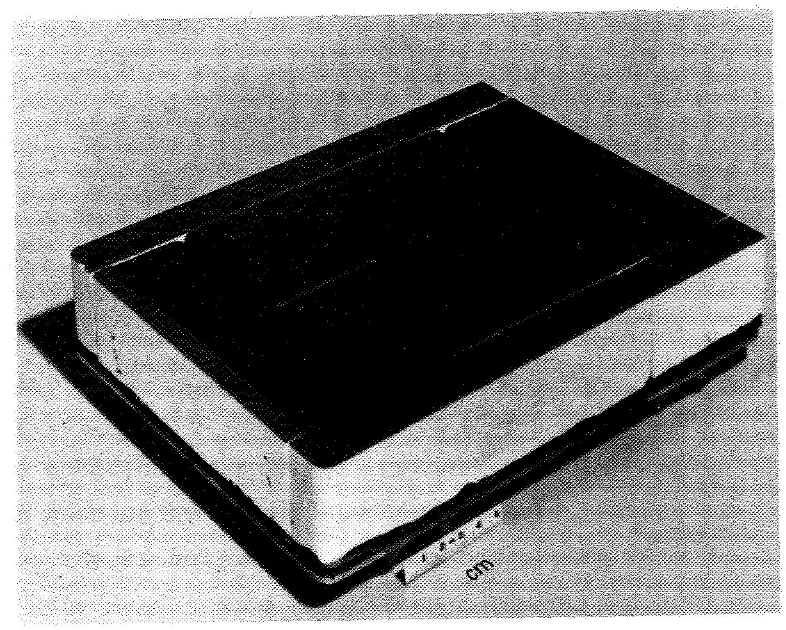
(Figure 7)

An illustration and pre-test photograph of the General Electric REI-MOD 1A panel are shown in figure 7. The panel consisted of two 7.6 x 15.2 cm (3 x 6 inch) tiles of REI-MOD 1A insulation surrounded by smaller tile segments of the same material to form the gap configuration shown in the figure. The gaps were .25 cm (.100 inch) wide and of depth equal to the tile thickness. The tiles were bonded to a .20 cm (.080 inch) PD-200 foam pad which was, in turn, bonded to a .38 cm (.15 inch) aluminum plate. Five chromel-alumel thermocouples were located at the bottom of the gaps in the positions shown in the figure. Additional thermocouples were located at the backface of the tiles and on the aluminum plate. The General Electric Company supplied two similar panels for this investigation, one with unfilled gaps and the other filled with a silica omniweave gasket material. At the time of this writing the panel with the filled gaps had not been tested; therefore, only the results for the panel with unfilled gaps are reported.

GENERAL ELECTRIC REI-MOD IA PANEL



a) ILLUSTRATION



b) PRE-TEST PHOTOGRAPH

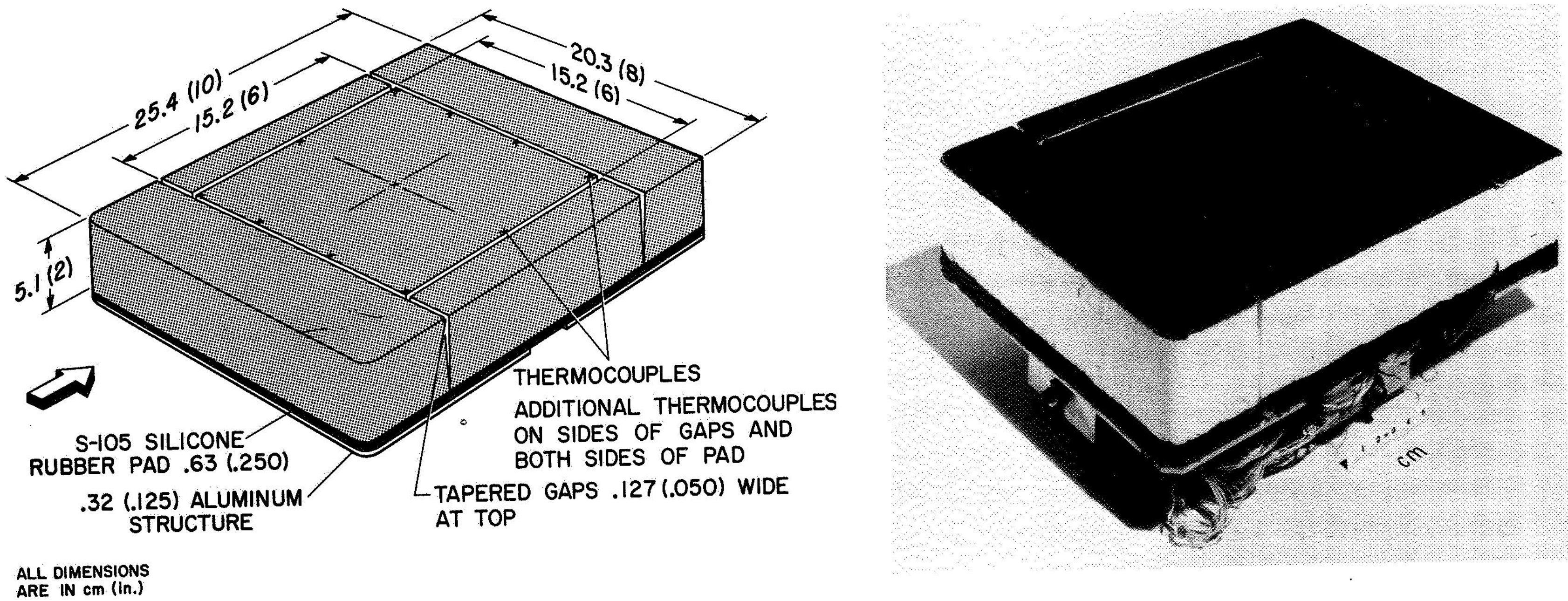
Figure 7

MCDONNELL DOUGLAS HCF-MOD III PANEL

(Figure 8)

An illustration and pre-test photograph of the McDonnell Douglas HCF-MOD III panel are shown in the accompanying figure. This panel consisted of a 15.2 x 15.2 cm (6 x 6 inch) HCF MOD-III tile surrounded by smaller tile segments of the same material. The tapered gaps were .13 cm (.050 inch) wide at the top. The tiles were bonded to a 0.63 cm (.250 inch) S-105 silicone rubber pad, which in turn was bonded to a .32 cm (.125 inch) aluminum plate. Ten platinum-platinum/10 percent rhodium thermocouples were located at the top edges of the 15.2 x 15.2 cm (6 x 6 inch) tile in the positions indicated. Chromel-alumel thermocouples were also located along the vertical wall of the tile at one gap position. Additional thermocouples were located in the rubber pad and on the aluminum panel. The McDonnell Douglas Company supplied two similar panels for this investigation, one having tiles 5.1 cm (2.0 inch) thick and the other 7.6 cm (3.0 inch) thick. At the time of this writing, the 7.6 cm thick panel had not been tested; therefore, only the results for the 5.1 cm thick panel are presented.

MCDONNELL DOUGLAS HCF-MOD III PANEL



(a) ILLUSTRATION

(b) PRE-TEST PHOTOGRAPH

Figure 8

LOCKHEED LI-1542 PANEL AFTER 6 CYCLES

(Figure 9)

A photograph taken of the Lockheed LI-1542 panel after six simulations is shown in figure 9. The air flow over the panel was from left to right as viewed in the photograph. Because of manufacturing and assembly tolerances, this panel had two forward facing steps on the outer windward edges of the rear tile segment. The largest of these steps was .13 cm (.050 inch). The higher heating which results from interaction with the relatively thin turbulent boundary layer resulted in local softening of the coating and substrate and is apparent to some extent in this figure. This local heating appeared to be self-aggravating because softening and resulting coating flow caused the step height to increase. The loss of coating exposed the low emittance tile material resulting in higher local temperatures and shrinkage which resulted in a small cavity. The inability of this cavity to radiate effectively caused more shrinkage and the tests were terminated after ten cycles. A photograph of the panel taken after ten cycles is shown in the next figure.

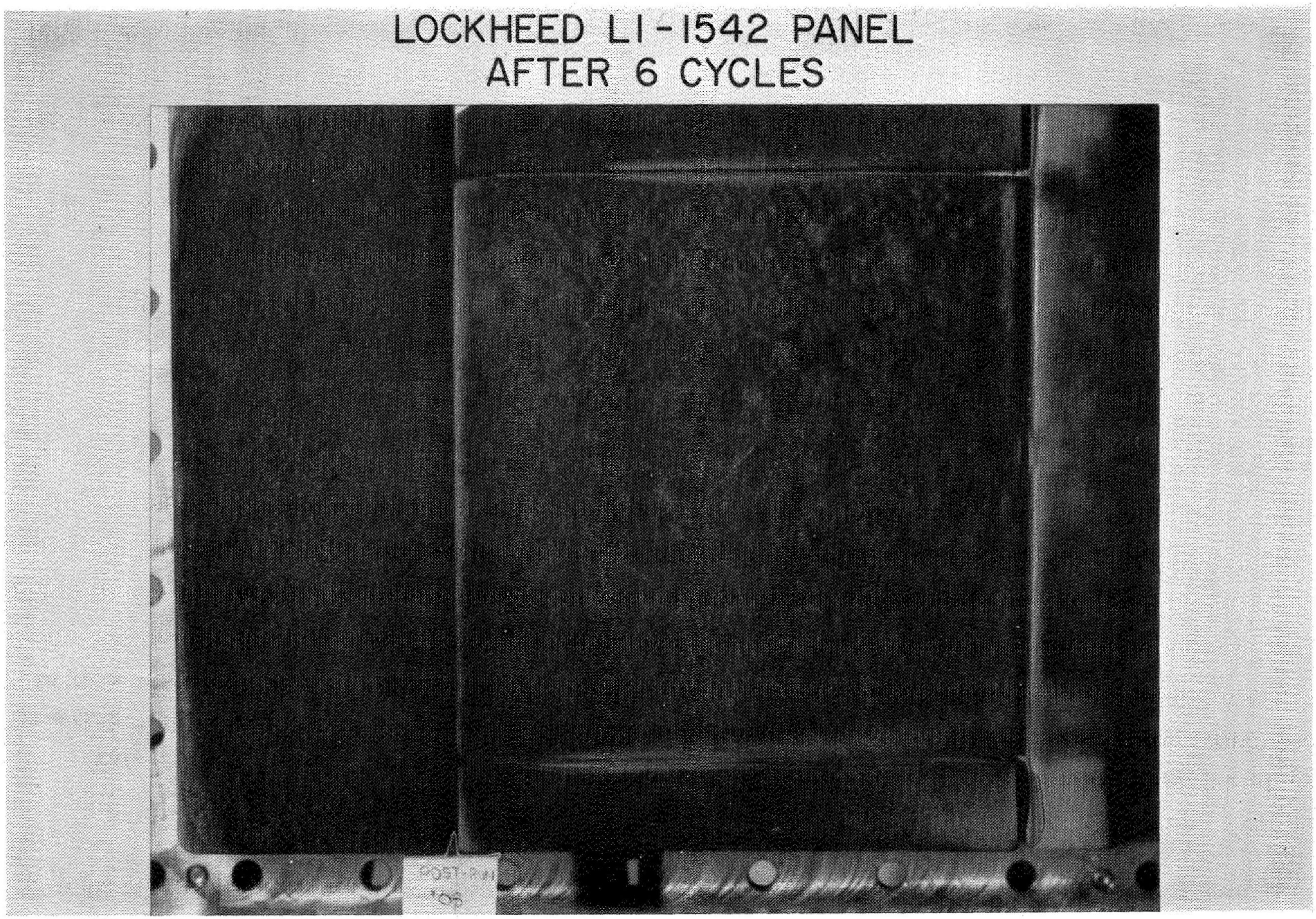


Figure 9

LOCKHEED LI-1542 PANEL AFTER 10 CYCLES

(Figure 10)

This figure presents the photograph of the Lockheed LI-1542 test panel after the 10 cycles of testing. The final result of the aggravated heating due to the forward facing steps is apparent in this figure.

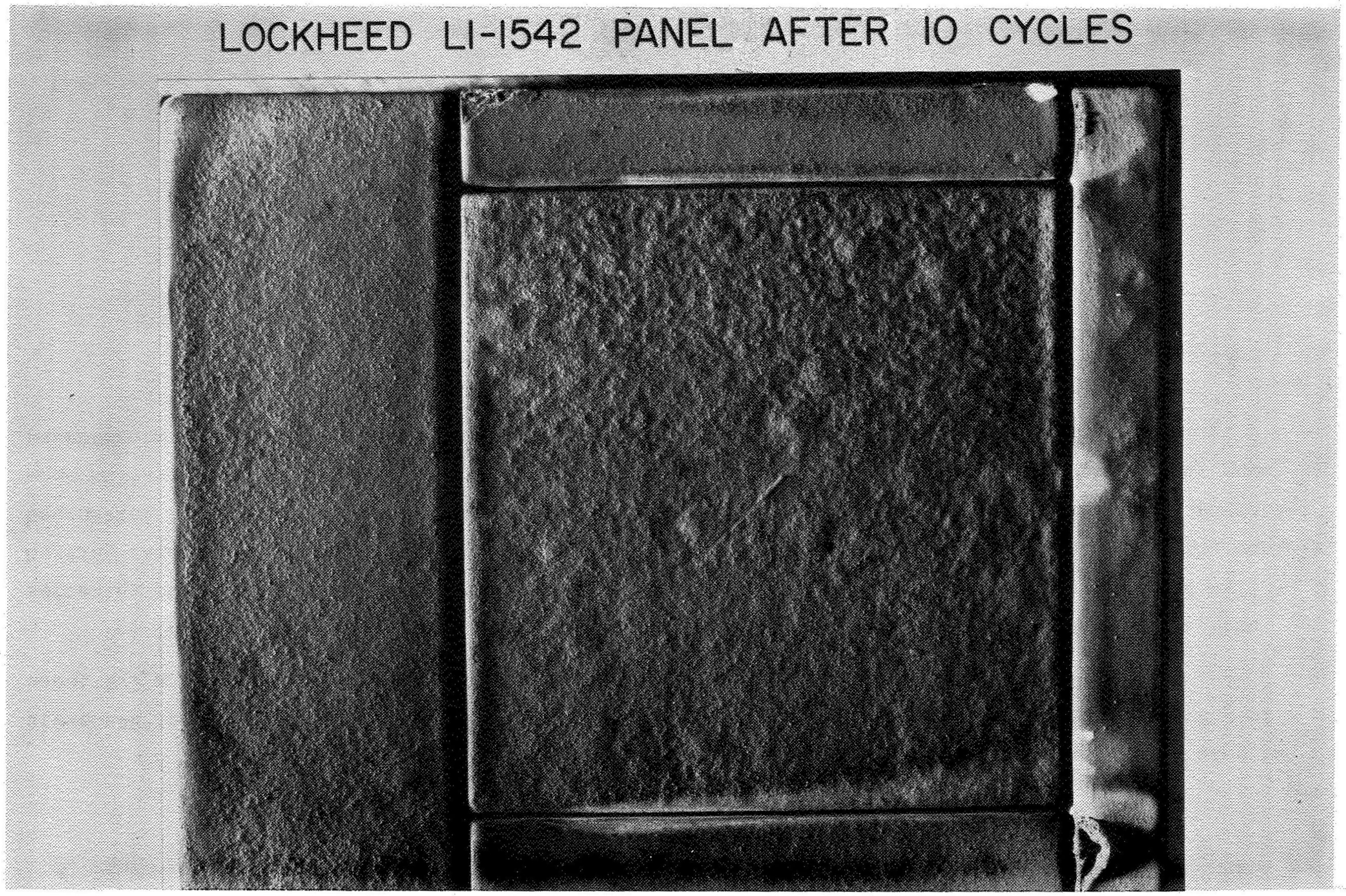


Figure 10

LOCKHEED LI-1542 REAR GUARD TILE AFTER 10 CYCLES

(Figure 11)

A close-up photograph of the area that was overheated due to the presence of the step is presented in this figure. A saw cut taken through the damaged section showed an oblong cavity of about 1.3 x 2.5 cm (1/2 x 1 inch) of inside dimension.

The temperature in the area that failed is estimated to be about 1920°K (3000°F), the softening point of silica glass. This implies a factor of about three increase in the cold wall heating rate in the vicinity of the step. Whether or not this could present a problem on the vehicle, because of its thicker boundary layer, is not clear. It is clear, however, that this is a potential mode of failure. The maximum size of steps permissible on the vehicle must be determined by more experimentation to determine the boundary layer thickness parameter that governs the heating.

LOCKHEED LI-1542 REAR GUARD
TILE AFTER 10 CYCLES

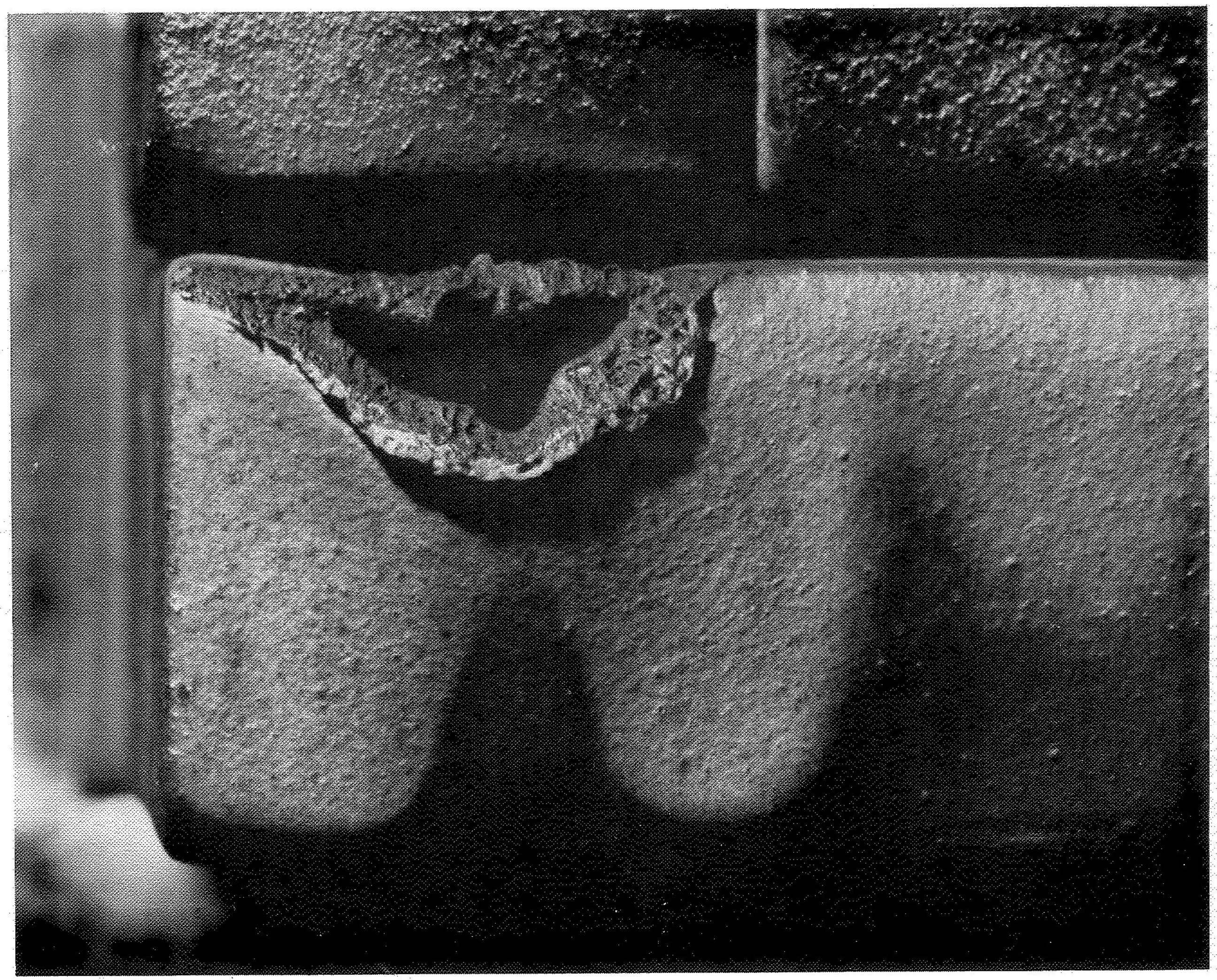


Figure 11

GENERAL ELECTRIC REI-MOD 1A PANEL AFTER 13 CYCLES

(Figure 12)

A photograph of the General Electric REI-MOD 1A panel after 13 simulations is shown in figure 12. At the leading edge of the lower 7.6 x 15.2 cm (3 x 6 inch) tile is an area which has a "paint peel" texture. This area, which could be interpreted as a failure of one or more layers of coating appeared very early in the tests but did not seem to worsen. Another area, near the leading edge of the upper 7.6 x 15.2 cm (3 x 6 inch) tile of the figure showed visible signs of cracking. This will be shown in more detail in the section on nondestructive testing. Visual inspection of the silicone rubber, which can be seen at the bottoms of the gaps after the test, showed no apparent signs of deterioration. A small area, on the thin strip at the trailing edge of the panel, lost its coating due to handling during the course of the tests but no adverse effect was observed.

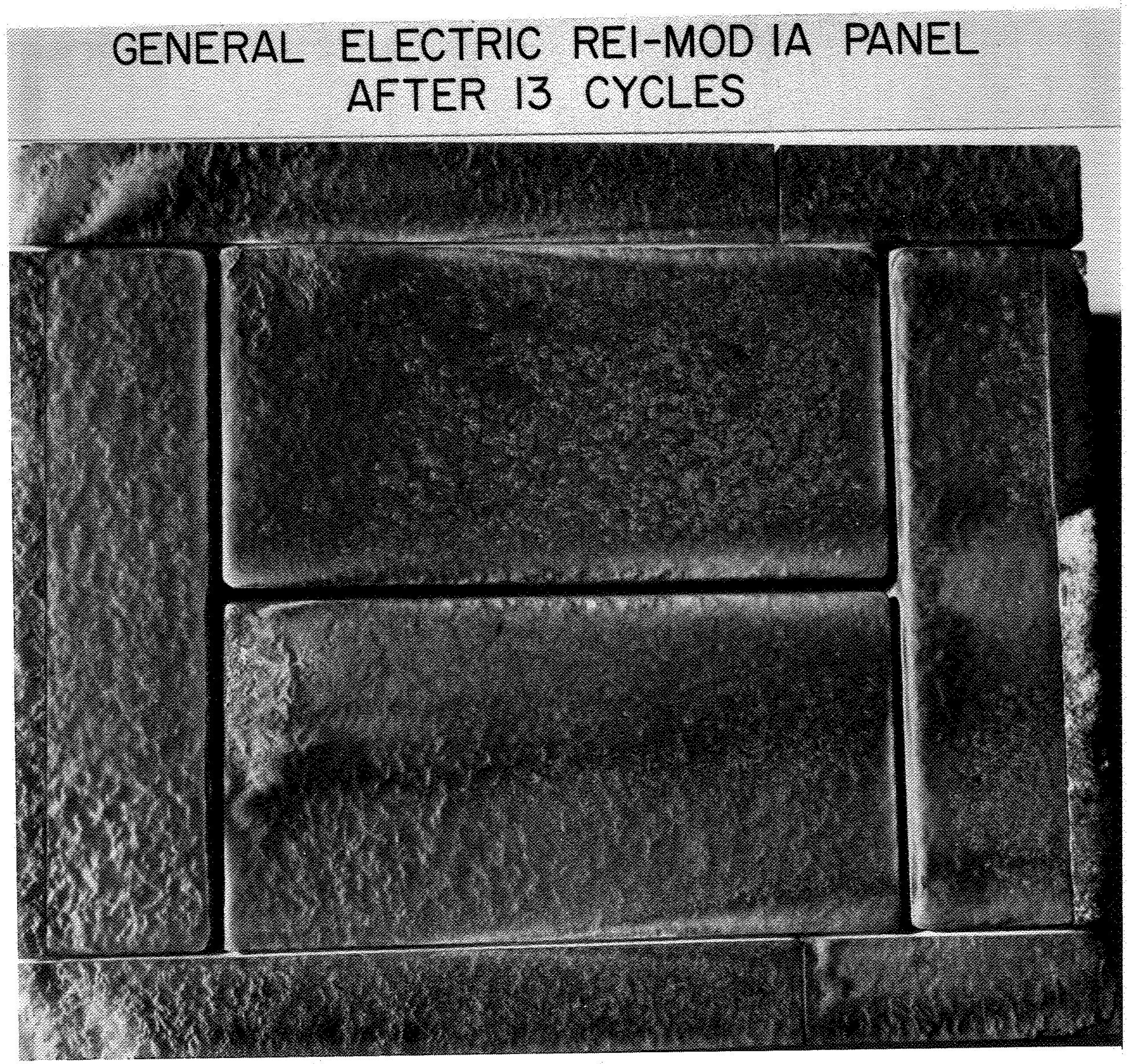


Figure 12

MCDONNELL DOUGLAS HCF-MOD III PANEL AFTER 14 CYCLES

(Figure 13)

A photograph of the McDonnell Douglas HCF-MOD III panel after 14 simulations is shown in this figure. Cracks in the 15.2 x 15.2 cm (6 x 6 inch) tile are clearly visible in the photograph taken after removal from the facility. The cause of the color gradations in the vicinity of the cracked area is not known. Cracking in this panel was detected by visual inspection after the first exposure. Despite the presence of cracks, the tests were continued for another 13 cycles with only a small amount of additional cracking noted.

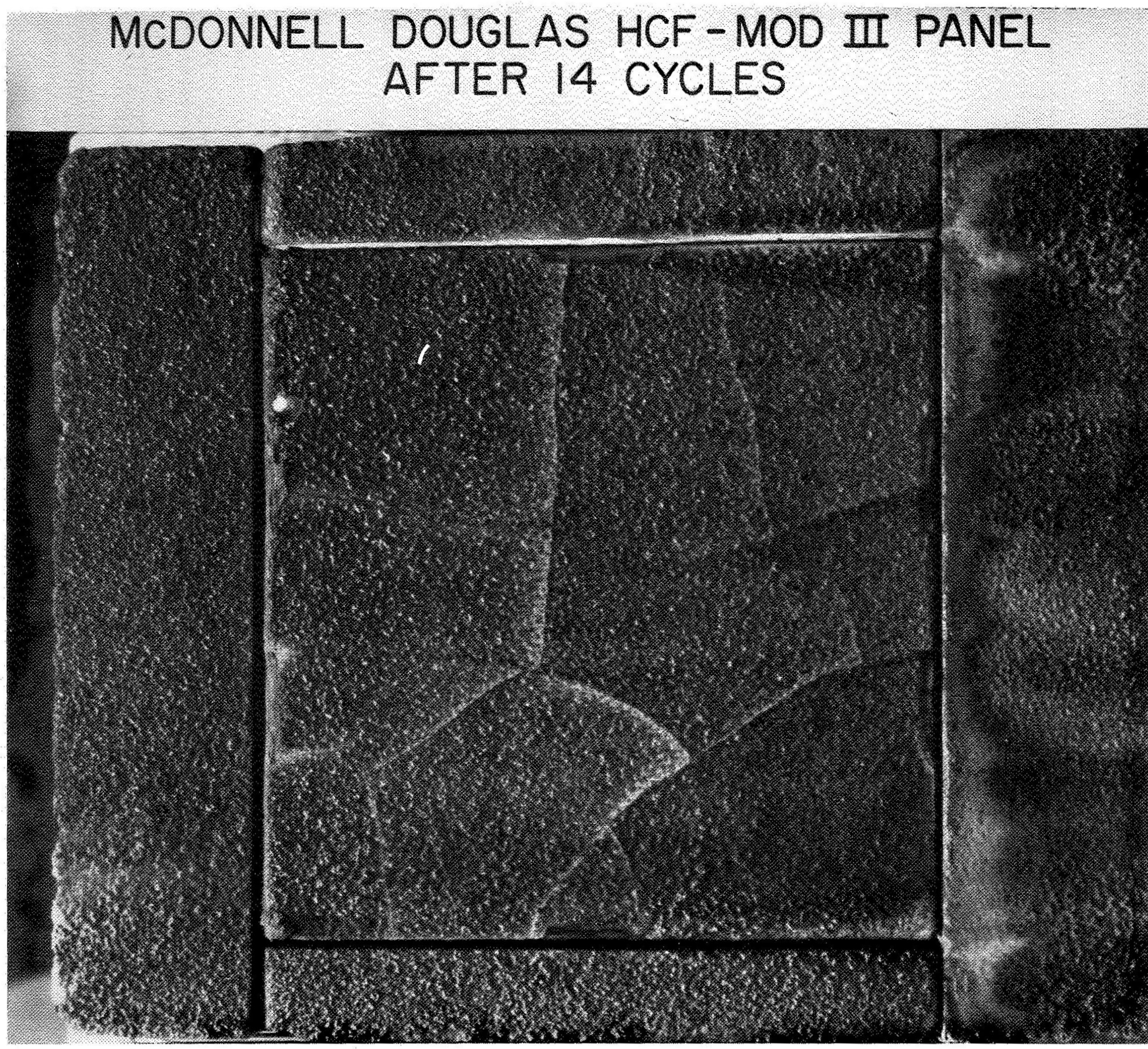


Figure 13

TEMPERATURE HISTORIES AT BOTTOM OF GAPS
LOCKHEED LI-1542 PANEL

(Figure 14)

The temperatures measured at the bottom of two streamwise and two spanwise gaps for the Lockheed panel are shown in this figure. The results are compared with a reference temperature measured at the center of the tile at the same depth and which is unaffected by gap heating. The differences between the measured gap temperatures and the reference temperature provide a measure of the heating due to the presence of the gap. The temperatures measured in the two spanwise gaps are slightly higher than the reference temperature. The temperature in one of the streamwise gaps is as much as 111°K (200°F) lower than the reference temperature. The temperature in the other streamwise gap in the region of the forward facing step is considerably higher than the reference temperature because of the aggravated heating in this area. In the absence of steps, no excessive heating problems are evident in this gap design.

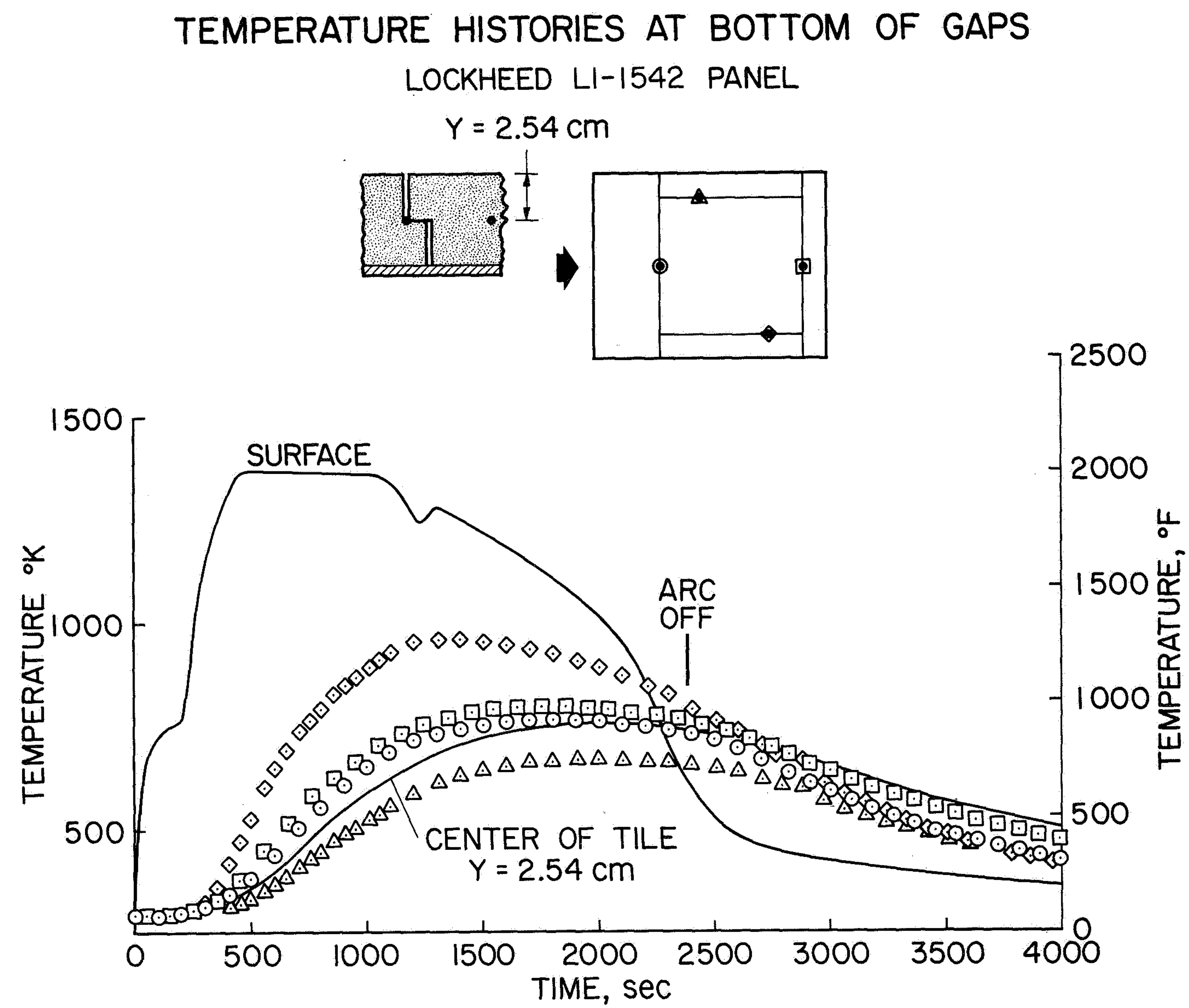

TEMPERATURE HISTORIES AT BOTTOM OF GAPS
LOCKHEED LI-1542 PANEL
Y = 2.54 cm
SURFACE
ARC
OFF
CENTER OF TILE
Y = 2.54 cm
TEMPERATURE °K
TEMPERATURE, °F
TIME, sec
1500
1000
500
2500
2000
1500
1000
500
0
0
500
1000
1500
2000
2500
3000
3500
4000

Figure 14

MEASURED AND PREDICTED TEMPERATURE HISTORIES

LOCKHEED LI-1542 PANEL

(Figure 15)

The surface and in-depth temperature response for the Lockheed LI-1542 panel is shown in this figure. The results are compared with predictions made using a one-dimensional heat transfer program that accounts for thermophysical property variations with temperature and pressure. The predictions account for the nonadiabatic conditions at the rear of the aluminum support plate. The calculations tend to overpredict the in-depth temperatures but, in general, are in good agreement. The properties used in the calculations were obtained from the Midterm Review, Space Shuttle Thermal Protection System Development (LMSC-A995708, SS-1135). Thermal conductivities for a pressure of 100 N/m^2 (.001 atm) were used in the calculations. The comparison between the measurements and predictions lead to the conclusion that the values of density, specific heat, and pressure-dependent thermal conductivity as published in the above document tend to give somewhat conservative results.

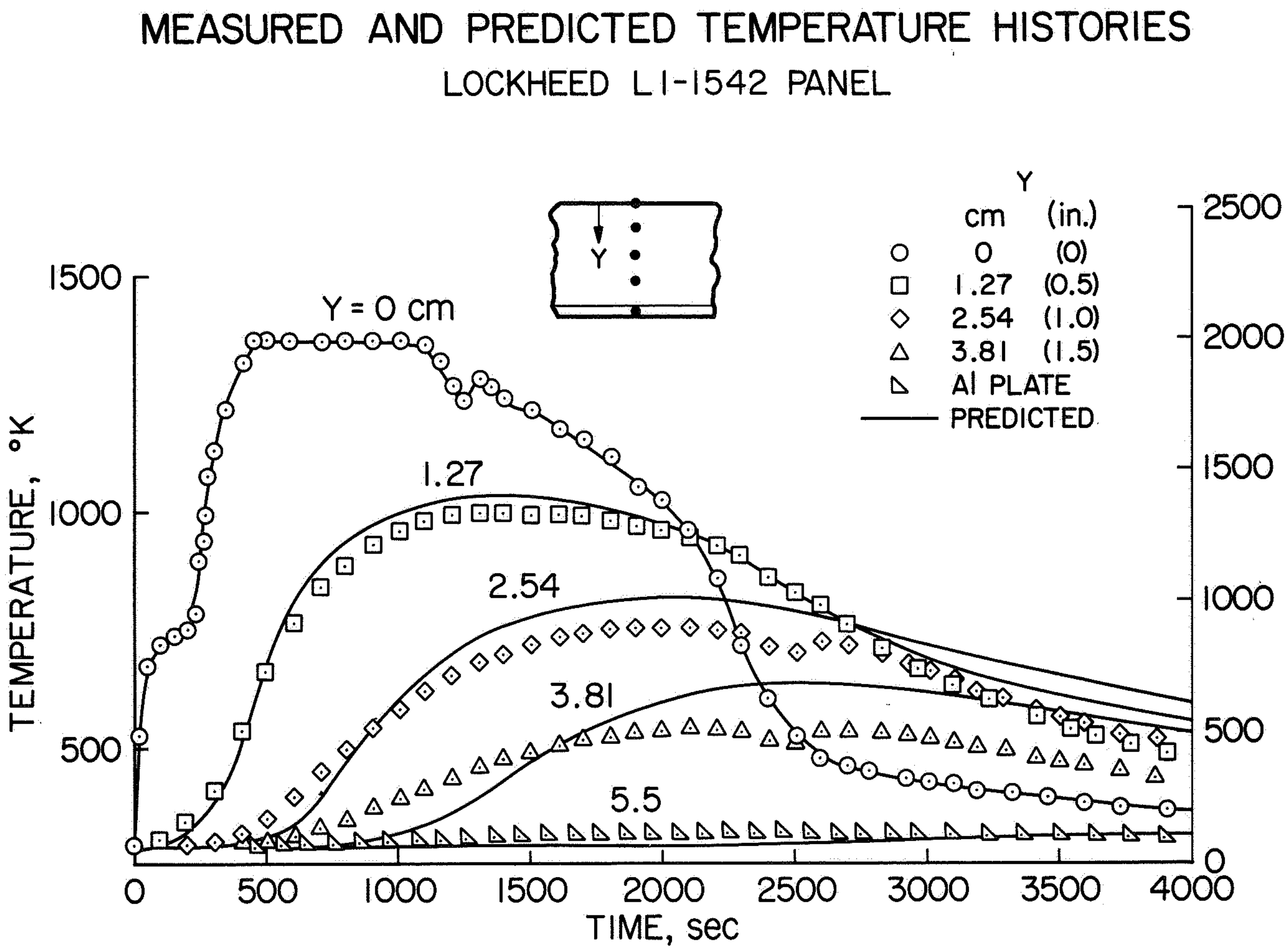

MEASURED AND PREDICTED TEMPERATURE HISTORIES
LOCKHEED LI-1542 PANEL
Y
cm (in.)
0 (0)
1.27 (0.5)
2.54 (1.0)
3.81 (1.5)
Al PLATE
PREDICTED
Y = 0 cm
1.27
2.54
3.81
5.5
TEMPERATURE, °K
TEMPERATURE, °F
TIME, sec

Figure 15

TEMPERATURE HISTORIES

GENERAL ELECTRIC REI-MOD 1A PANEL

(Figure 16)

The measured temperature histories for the General Electric REI-MOD 1A panel are shown in the accompanying figure. Optical pyrometer measurements (solid circular symbols) were made on the rear tile segment (see sketch) using an Infrared Industries TD-9 optical pyrometer with emissivity set at 0.8. The spacing of the observation ports (7.6 cm or 3.0 inch) precluded measurements being made on the larger 7.6 x 15.2 cm (3 x 6 inch) tiles. A measure of the heating at the bottom of the gaps can be made by comparing these temperatures with a reference temperature at the same depth that is unaffected by gap heating. It can be seen that the temperatures at the bottom of the gaps are as much as 167°K (300°F) higher than the reference temperature. The area most affected appears to be at the upstream end of the gap. It is also noteworthy that the maximum temperature at one point reached 590°K (600°F), the maximum use temperature for the adhesive used to bond these tiles to the substrate.

TEMPERATURE HISTORIES

GENERAL ELECTRIC REI-MOD IA PANEL

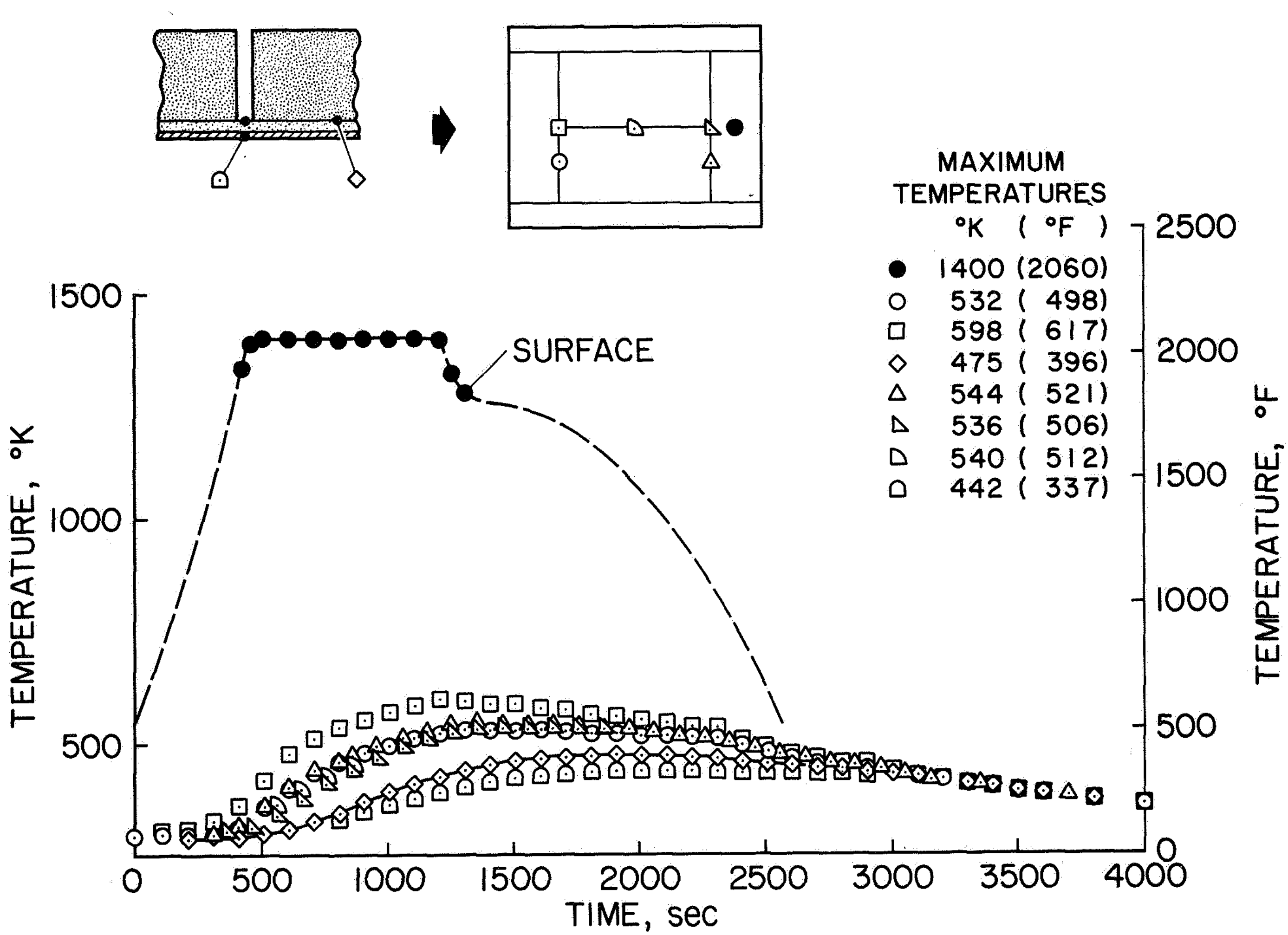


Figure 16

TEMPERATURE HISTORIES

MCDONNELL DOUGLAS HCF-MOD III PANEL

(Figure 17)

The measured temperatures along the top edges of the 15.2 x 15.2 cm (6 x 6 inch) tile and at the bottom of the gap of the McDonnell Douglas HCF-MOD III panel are shown in the accompanying figure. The temperatures at the edges of the tile that form streamwise and spanwise gaps can be compared with a reference temperature unaffected by gap heating measured at the center of the top surface of the tile (solid circular symbols) using an optical pyrometer (Infrared Industries TD-9 with emissivity set at 0.8). In general, the temperatures at the downstream side of spanwise gaps are higher than the reference temperature, while the temperatures at the upstream side of spanwise gaps are lower than the reference temperature. The temperatures at the top edges of gaps aligned with the stream are also lower than the reference temperature. A measure of the heating at the bottom of the gap can be made by comparing this temperature with a reference temperature at the same depth in an area unaffected by the gap. In general, the temperature at the bottom of the gap is as much as 56°K (100°F) higher than this reference temperature. The maximum temperature at the bottom of the gap was 530°K (490°F), about 56°K (100°F) lower than the maximum use temperature of the adhesive used to bond these tiles to the substrate.

TEMPERATURE HISTORIES

McDONNELL DOUGLAS HCF-MOD III PANEL

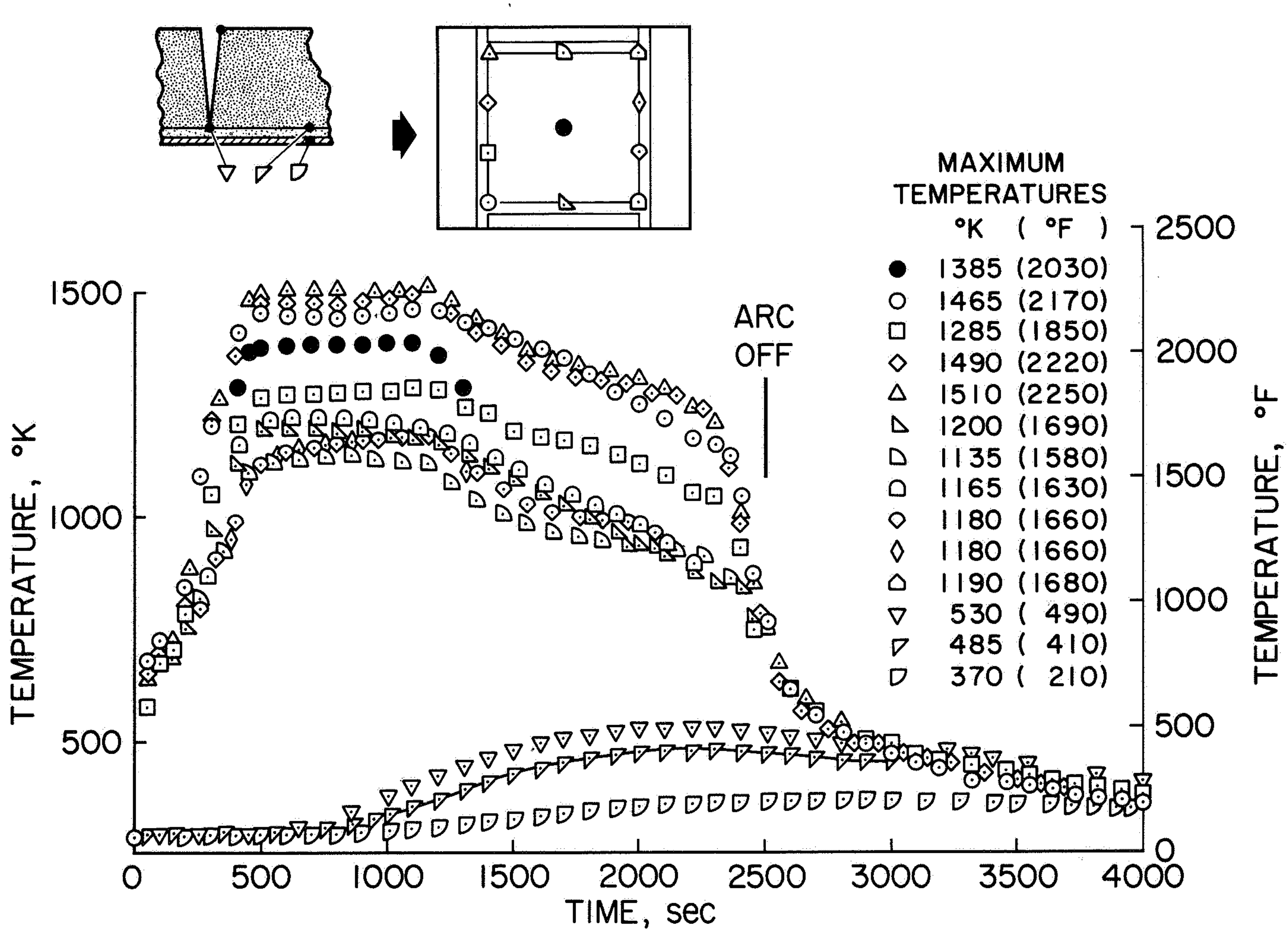


Figure 17

TEMPERATURE HISTORIES ALONG GAP WALL
MCDONNELL DOUGLAS HCF-MOD III PANEL

(Figure 18)

The temperature histories along the vertical gap wall of the McDonnell Douglas HCF-MOD III panel at a point along the leading edge of the 15.2 x 15.2 cm (6 x 6 inch) tile are shown in this figure. (See sketch for location of thermocouples.) For purposes of comparison, the temperatures measured using the TD-9 optical pyrometer are also shown (solid circular symbols).

TEMPERATURE HISTORIES ALONG GAP WALL

McDONNELL DOUGLAS HCF-MOD III PANEL

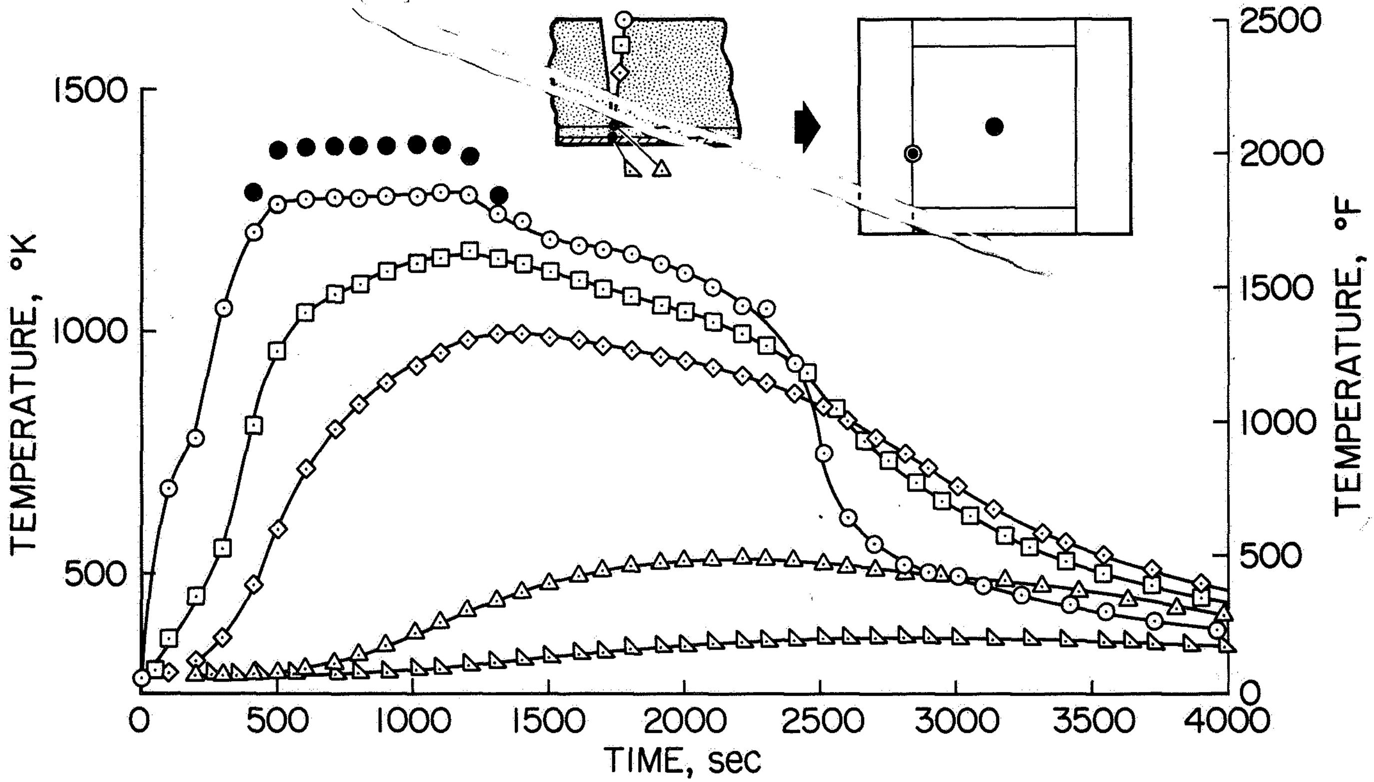


Figure 18

NONDESTRUCTIVE CRACK DETECTION
GENERAL ELECTRIC PANEL

(Figure 19)

The next four figures illustrate the results of surface crack detection using the technique developed at NASA-Manned Spacecraft Center. This technique consists of applying highly volatile acetaldehyde to the surfaces of the tiles. Some of this liquid penetrates the cracks (if any) while the remainder volatilizes. After waiting an appropriate time, chemically sensitized paper is placed over the tile. Vapor emanating from the cracks causes the paper to turn blue. This technique determines the presence of surface cracks or porosity. The depth of the cracks must be determined by other means, such as X-ray methods.

The cracks detected in the General Electric REI-MOD 1A panel after 13 simulations are depicted in figure 19. No cracking was observed in the lower tile. However, an area near the leading edge of this tile reacted strongly to the acetaldehyde test indicating possibly many microcracks or porosity of the coating. It should be emphasized that these 7.6 x 15.2 cm (3 x 6 inch) tiles were the smallest in this test series. Cracking due to thermal stresses is highly size dependent.

NONDESTRUCTIVE CRACK DETECTION
GENERAL ELECTRIC PANEL

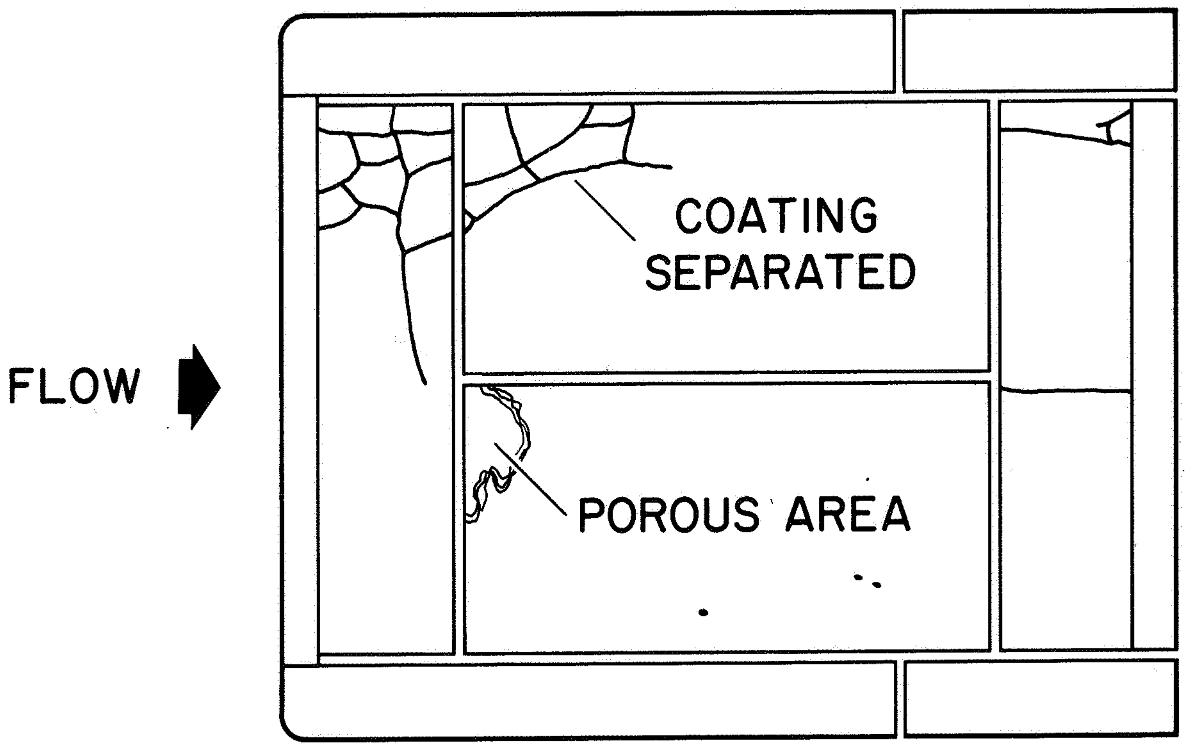


Figure 19

NONDESTRUCTIVE CRACK DETECTION

MCDONNELL DOUGLAS PANEL

(Figure 20)

The cracks detected in the McDonnell Douglas HCF-MOD III panel after 13 simulations are depicted in figure 20. Most of this cracking was visually detected after the first arc-jet simulation.

NONDESTRUCTIVE CRACK DETECTION
McDONNELL DOUGLAS PANEL

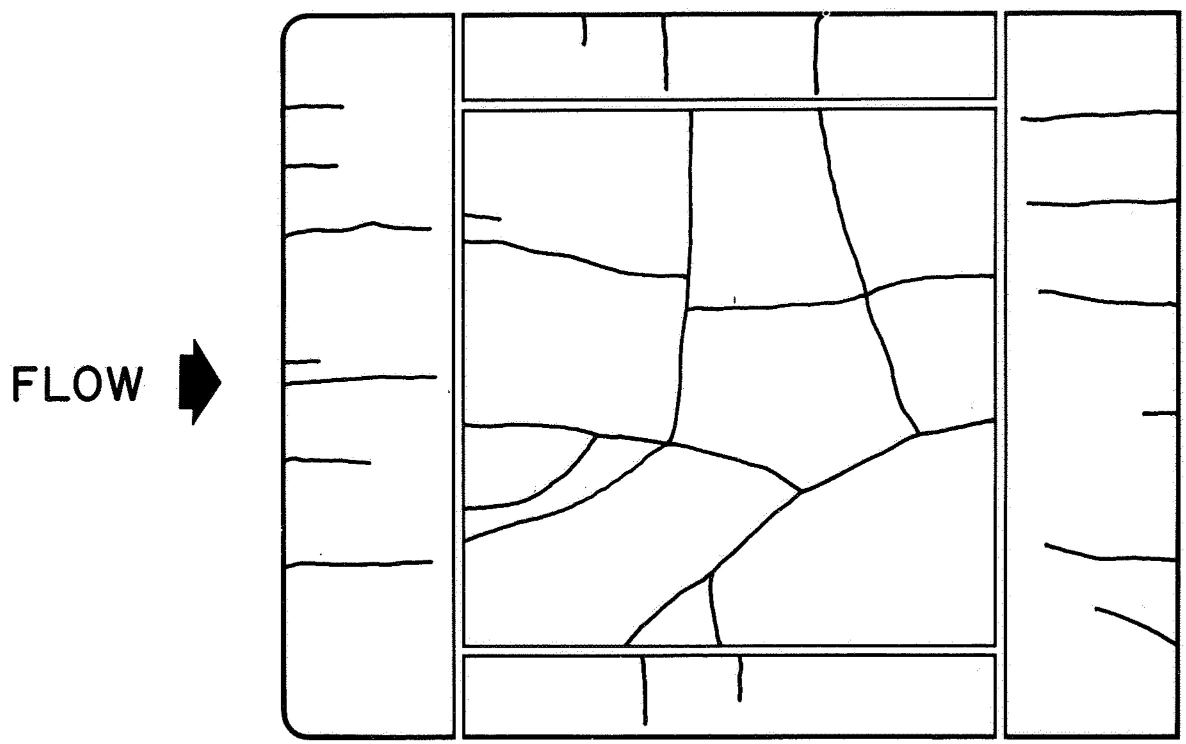


Figure 20

NONDESTRUCTIVE CRACK DETECTION

LOCKHEED PANEL

(Figure 21)

The cracks detected on the Lockheed LI-1542 panel using the acetaldehyde technique are depicted in this figure. The majority of these cracks are in the vicinity of the surface thermocouples. However, immediately after application of the acetaldehyde, small cracks could be seen visually that were not detectable on the sensitized paper.

NONDESTRUCTIVE CRACK DETECTION
LOCKHEED PANEL

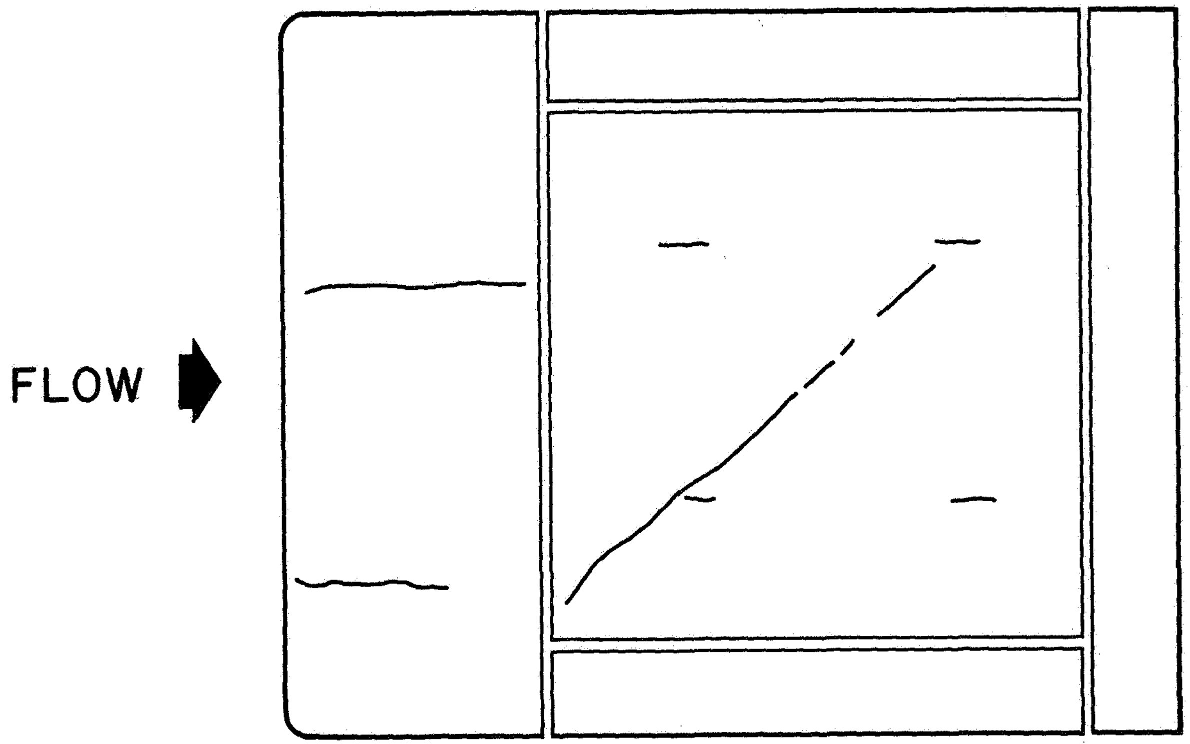


Figure 21

NONDESTRUCTIVE CRACK DETECTION OF LOCKHEED PANEL
AFTER APPLICATION OF ACETALDEHYDE

(Figure 22)

This figure presents a photograph of the Lockheed LI-1542 panel where the cracks that were not detectable on the sensitized paper are clearly evident. However, it should be emphasized that, at the time of these experiments, Ames Research Center had a minimum of experience using this technique. These small cracks might have easily been detected by the more experienced experimenters at the Manned Spacecraft Center where the technique was developed.

NONDESTRUCTIVE CRACK DETECTION
LOCKHEED PANEL AFTER APPLICATION OF ACETALDEHYDE

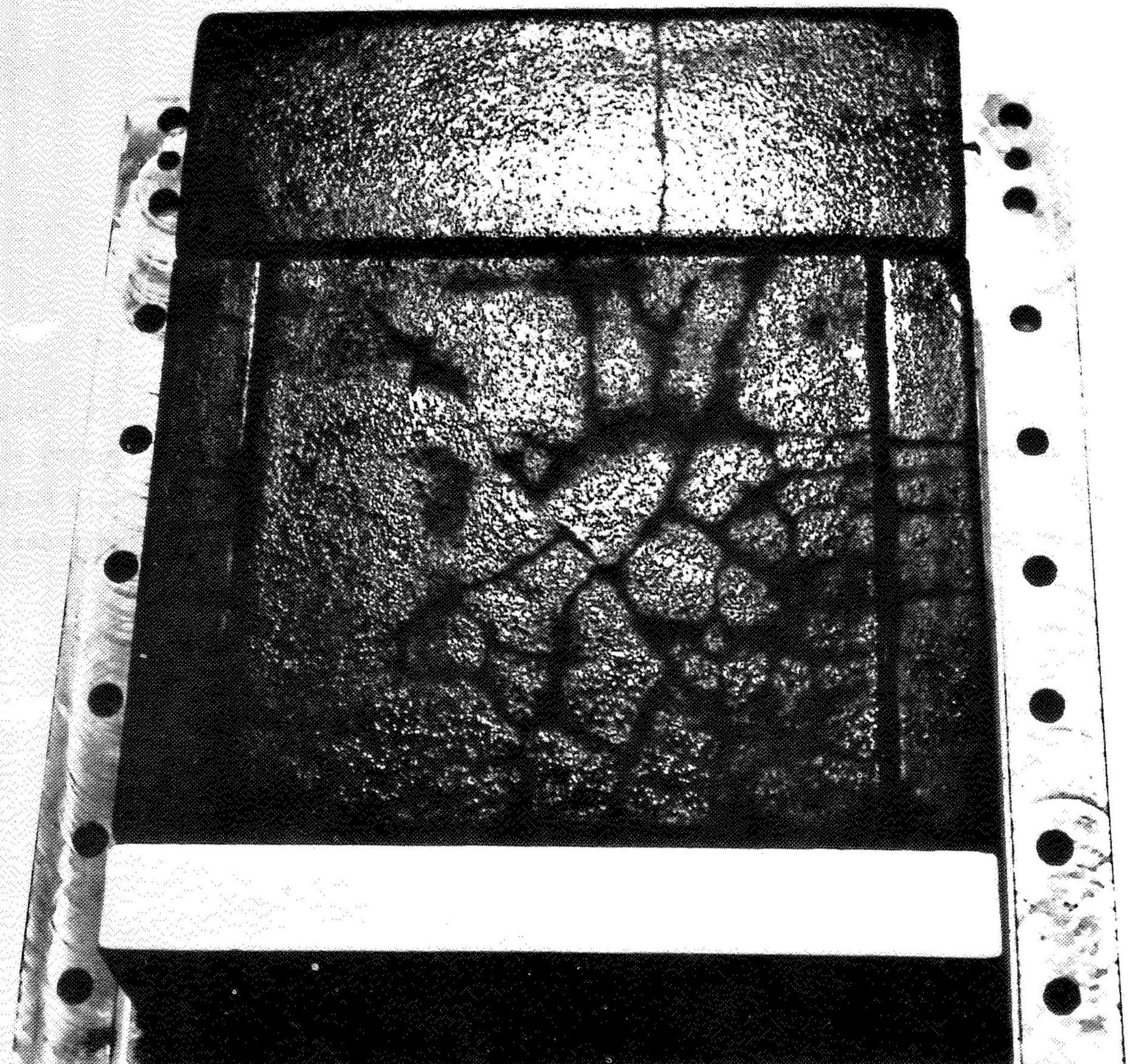


Figure 22

WATER REPELLENCY TEST OF LOCKHEED PANEL

(Figure 23)

Water repellency tests of the panels after arc-jet exposure are shown in the next three figures. This test consisted simply of applying drops of distilled water at various locations and observing the results. For the Lockheed LI-1542 panel shown in figure 23 there was water absorption at four locations after five minutes. After 25 minutes there was indication of water absorption at a total of about 12 locations.

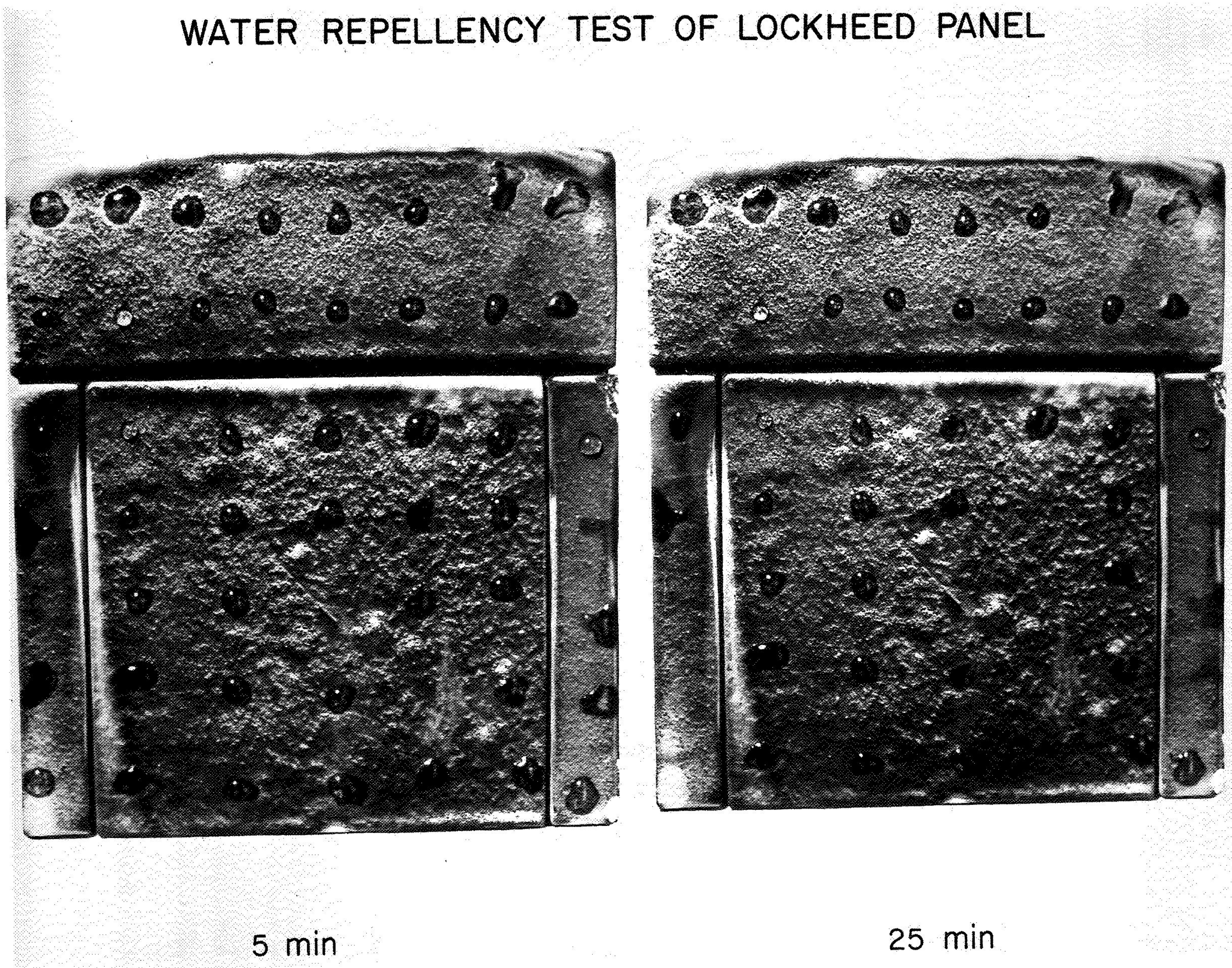


Figure 23

WATER REPELLENCY TEST OF MCDONNELL DOUGLAS PANEL

(Figure 24)

The McDonnell Douglas HCF MOD-III panel shown in this figure showed no signs of absorbing water, even when the droplets were placed over visible cracks.

WATER REPELLENCY TEST OF McDONNELL DOUGLAS PANEL

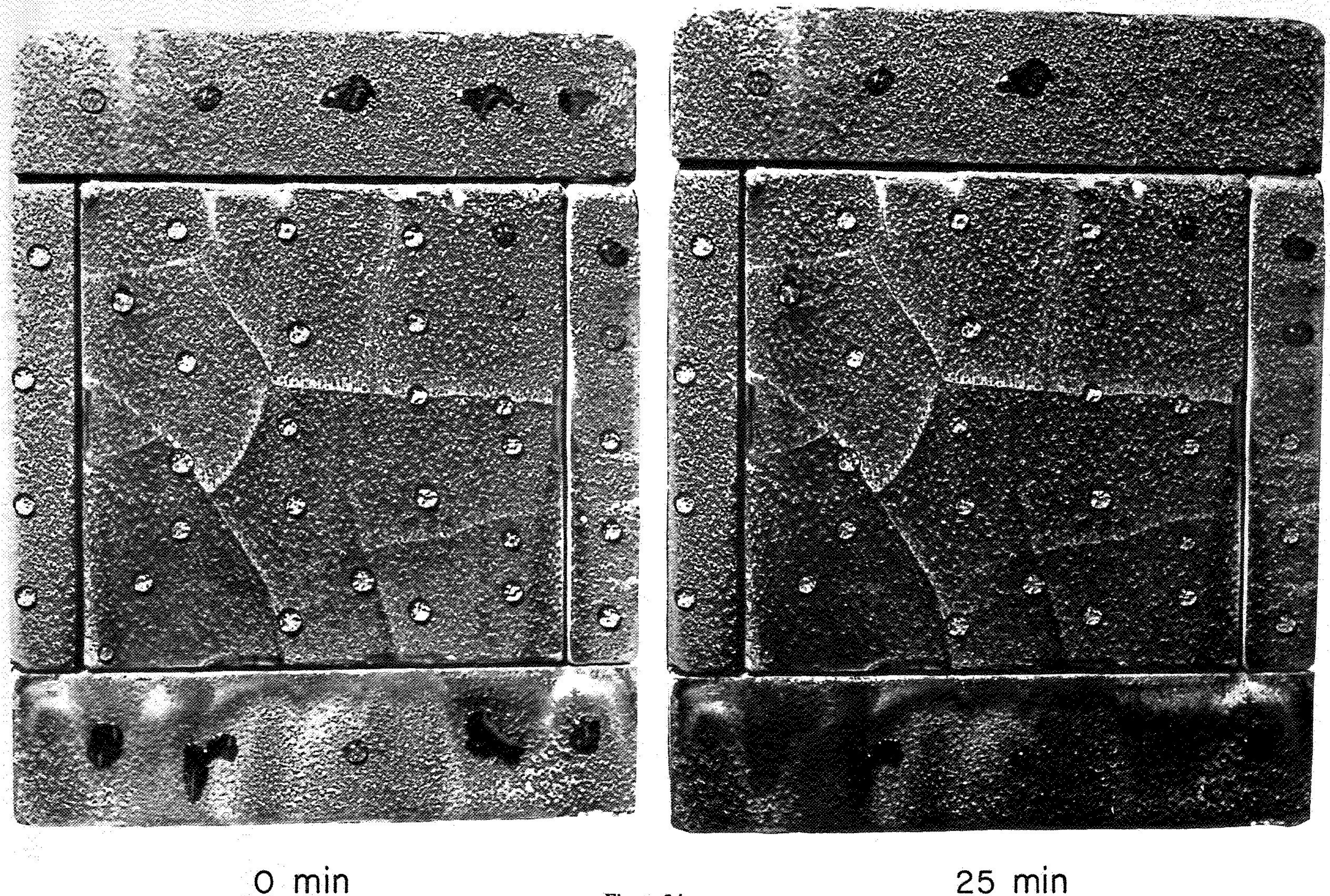


Figure 24

WATER REPELLENCY TEST OF GENERAL ELECTRIC PANEL

(Figure 25)

The General Electric REI MOD-1A panel shown in this figure also showed no signs of absorbing water, even when droplets were placed on the area which had lost the surface coating. In some cases, water droplets would not penetrate the uncoated edges of panels prior to arc-jet exposure.

This simple test may not be good measure of waterproofness; however, based on the observations, some comments are in order. First, if water droplets penetrate easily, the coating is certainly not waterproof. Second, if the droplets wet the coating and spread out evenly, the results are difficult to interpret. Third, the lack of penetration in cracks and even in uncoated areas is somewhat inconclusive. One possible interpretation of this lack of penetration, even in uncoated areas, is the presence of silicone oil at these sites. A possible source of silicone, if not present prior to the test, is volatilization from the bond area, which had been heated to several hundred degrees during the tests. Another possible reason is the condensation of stream impurities on the tile surfaces.

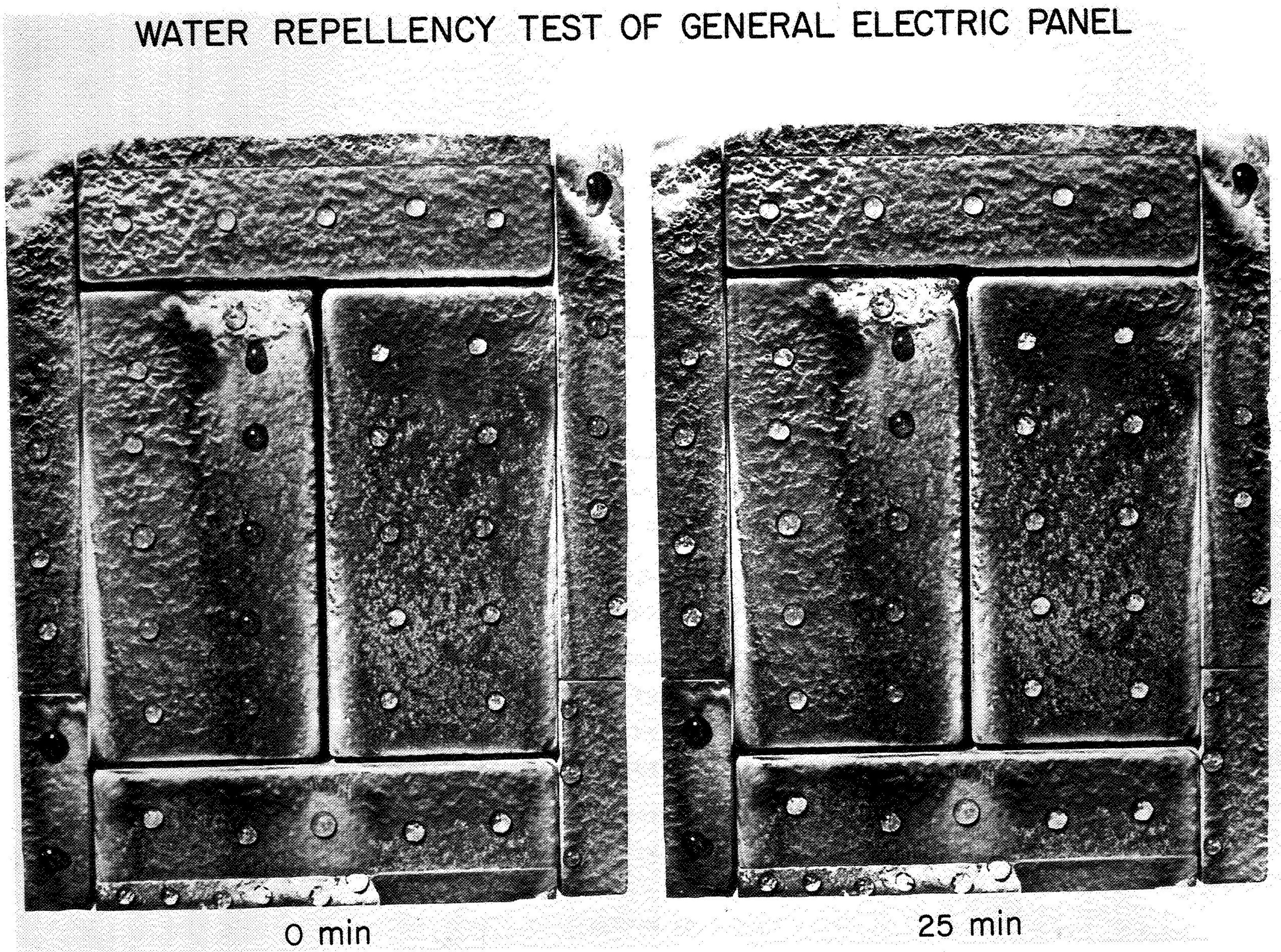

WATER REPELLENCY TEST OF GENERAL ELECTRIC PANEL
0 min
25 min

Figure 25

CONCLUSIONS

(Figure 26)

1. Using the technique of mixing argon with air it is possible to closely simulate the temperature-time trajectory experienced by the Space Shuttle Vehicle in facilities of this type.

2. Gap heating appears to be highly dependent upon gap design. It is relatively low for the interlocking Lockheed design and tapered design of McDonnell Douglas. It is significantly higher for the wider, unfilled gap design of General Electric. While the filled gap design was not tested in this investigation, it is expected that the heating will be reduced significantly.

3. The heating rate appears to be significantly higher at the windward facing edges of flush tiles, while at the same time, being lower at the leeward and streamwise edges.

4. The heating rate is aggravated at forward facing steps. This heating, however, is highly dependent on step heights relative to some characteristic thickness of the boundary layer. Further tests are required to identify the magnitude of this heating as it relates to the Space Shuttle Vehicle and its boundary layer characteristics.

5. Cracking of varying degrees was observed on all the RSI panels tested. These ranged from numerous fine cracks on the Lockheed panel to numerous larger cracks on the McDonnell Douglas panel.

CONCLUSIONS

- GOOD TRAJECTORY TEMPERATURE - TIME SIMULATION ACHIEVED USING ARGON - AIR TECHNIQUE
- GAP HEATING HIGHLY DEPENDENT UPON GAP GEOMETRY
- HEATING SIGNIFICANTLY HIGHER AT WINDWARD FACING EDGES OF FLUSH TILES
- HEATING AGGRAVATED AT FORWARD FACING STEPS - FURTHER TESTS ARE REQUIRED TO ESTABLISH DESIGN CRITERIA
- CRACKING OF VARYING DEGREES OBSERVED ON ALL PANELS

Figure 26